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Filtration of 'Giardia' Cysts and Other Substances. Volume 1 Diatomaceous Earth Filtration

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FILTRATION OF GIARDIA CYSTS AND OTHER SUBSTANCES
VOLUME 1: DIATOMACEOUS EARTH FILTRATION

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16. ABSTRACT

The effectiveness of diatomaceous earth filtration of drinking water was studied under various operating conditions for removal of Giardia cysts, total coliform bacteria, standard plate count bacteria, turbidity, and particles. Seven grades of diatomaceous earth were used. Temperatures ranged from 5° to 19°C, and concentrations of Giardia cysts and bacteria were varied over two or more log cycles.

Diatomaceous earth filtration is an effective process for water treatment. Giardia cyst removals were greater than 99.9 percent for all grades of diatomaceous earth tested, for hydraulic loading rates of 2.44 to 9.76 m/hr, and for all temperatures tested. Percent reductions in total coliform bacteria, standard plate count bacteria, and turbidity are influenced strongly by the grade of diatomaceous earth used. The coarsest grades of diatomaceous earth recommended for water treatment (e.g., C-545) will remove greater than 99 percent of Giardia cysts, 95 percent of cyst-sized particles, 20 to 35 percent of coliform bacteria, 40 to 70 percent of heterotrophic bacteria, and 12 to 16 percent of the turbidity from Horsetooth Reservoir water. The use of the finest grade of diatomaceous earth (i.e., Filter-Cel), or the use of the coarse grades with alum coating, will increase the effectiveness of the process, resulting in 99.9 percent removals of bacteria and 98-percent removals of turbidity.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

Giardiasis is an intestinal disease reported with increasing frequency especially in the western and northeastern United States. The disease is caused by ingestion of cysts of the protozoan Giardia lamblia. The cysts are commonly found in the cold clear streams of mountain environments, which are used as a source water supply by many communities. This report investigates the effectiveness of diatomaceous earth filtration in removal of Giardia cysts and other substances of concern, delineating the role of selected design criteria and operating conditions. Diatomaceous earth filtration is examined as a part of the EPA research program focused on water treatment problems of small communities.

Francis T. Mayo, Director
Municipal Environmental
Research Laboratory

ABSTRACT

DIATOMACEOUS EARTH FILTRATION OF GIARDIA CYSTS AND OTHER SUBSTANCES

The effectiveness of diatomaceous earth filtration of drinking water was studied under various operating conditions for removal of Giardia lamblia cysts, total coliform bacteria, standard plate count bacteria, turbidity, and particles. Hydraulic loading rates imposed were 2.44, 4.88, and 9.76 m/hr (1, 2, and 4 gpm/ft^2). Seven grades of diatomaceous earth were used. Temperatures ranged from 5° to 19°C, and concentrations of Giardia cysts and bacteria were varied over two or more log cycles.

Giardia lamblia is a protozoan prevalent in the clear, cool waters characteristic of the Rocky Mountain region. This organism causes giardiasis, a harmful but nonfatal intestinal disease. Many communities use water from these Rocky Mountain streams, which are considered pristine pure because they look aesthetically pleasing and will meet the 1-NTU turbidity water quality standard. How to treat these waters has become an important concern over the last few years as outbreaks of giardiasis have occurred. Economical and effective filtration systems are needed for the removal of Giardia cysts. Designs appropriate for small water systems are particularly needed. Diatomaceous earth filtration was one system studied for such application.

This study shows that diatomaceous earth filtration is an effective process for water treatment. Giardia cyst removals were greater than 99.9 percent for all grades of diatomaceous earth tested, for hydraulic loading rates of 2.44 to 9.76 m/hr, and for all temperatures tested. Percent reductions in total coliform bacteria, standard plate count bacteria, and turbidity are influenced strongly by the grade of diatomaceous earth used. The coarsest grades of diatomaceous earth recommended for water treatment (e.g., C-545) will remove greater than 99 percent of Giardia cysts, 95 percent of cyst-sized particles, 20 to 35 percent of coliform bacteria, 40 to 70 percent of heterotrophic bacteria, and 12 to 16 percent of the turbidity from Horsetooth Reservoir water. The use of the finest grade of diatomaceous earth (i.e., Filter-Cel), or the use of the coarse grades with alum coating, will increase the effectiveness of the process, resulting in 99.9 percent removals of bacteria and 98-percent removals of turbidity.

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SECTION 1

REVIEW OF DIATOMACEOUS EARTH FILTRATION

Synopsis

Diatomaceous earth filtration is a process that employs (1) a precoat filter cake consisting of a 3- to 5-mm thick layer of powder-sized diatomaceous earth filter media deposited on a support membrane (septum), and (2) a bodyfeed addition made up of the same or a different grade of filter media continuously fed to the filter vessel. The latter step maintains a constant permeability for the filter cake. In operation, the medium comprising the filter cake normally is discarded after each filtration cycle because it contains the removed particulate material.

The use of diatomaceous earth filtration for production of potable water began during World War II, when it was developed by the United States Army for field use. The process has been used since the 1870's, however, by industries requiring various applications of the filtration process. About half of the diatomaceous earth that is mined and processed is used in industrial and water treatment filtration applications. Other uses include its application as a filler, as an abrasive, as an absorbent, and as a thermal insulator.

Diatomaceous earth filtration has been used for municipal drinking water filtration since 1949. In the early 1960's, an AWWA Task Group chaired by E. R. Baumann, studied the municipal applications of diatomaceous earth filtration. They found that 88 municipalities had constructed diatomaceous earth filtration systems between 1953 and 1965. Most of the plants were built to remove turbidity causing particles, but some were built for iron and manganese removal or for lime-soda ash softening. The potable water production of these facilities ranged from 0.053 to 23 million liters per day (mL/d), or 0.014 to 6 mgd. Most of these installations provided drinking water supplies to smaller communities, usually with populations of less than 5,000. Thirteen of these 88 diatomaceous earth filtration plants were taken out of use by 1964 because they were either temporary installations or were not operated to give the performance intended. Information on the remaining 75 plants indicated that the diatomaceous earth filtration systems were performing satisfactorily. In 1974, the AWWA Diatomite Filtration Committee reported that about 145 plants were using the diatomaceous earth filtration process for potable water production. The early design mistakes of the diatomaceous earth filtration process included improper scale-up of equipment, excessive hydraulic loading rates, for example, 2-5.4 mm/s (3-8 gpm/ft^2), and improper bodyfeed concentration. Diatomaceous earth filtration design practice has come of age within the past 25 year period as a result of the basic foundation from research studies and experience in practice. The design and operating criteria thus developed have resulted in diatomaceous earth filtration being an effective and practical process for drinking water filtration.

Description of Diatomaceous Earth as a Material

Diatomaceous earth, also known as diatomite, diatomaceous silica, kieselguhr and tripolite, is a material process from a siliceous sedimentary rock formed from the fossil skeletal remains of microscopic aquatic plant life called diatoms. Diatoms are one-celled plants that make up the majority of floating plankton in waters. As a plant, they are at the bottom of the food chain, serving as the main source of nourishment for animals that live by filtering plankton from the water.

When diatoms die, their microscopic shells sink to the bottoms of water bodies. Hundreds of species, in various shapes and sizes were deposited millions of years ago in large shallow basins. The world's largest and known deposit is found in Lompoc, California. Some species of diatom fossils are shown in Figure 1. Figure 2 shows an electron micrograph of one diatom species at 2,000 magnification.

The main constituents of diatom skeletons include silica, alumina, iron, alkaline earth, and alkali metals. The high silica content, approximately 90% SiO_2, accounts for the unique characteristics of diatomaceous earth which make it odorless, tasteless, and almost chemically inert.

Diatomaceous earth is selectively quarried and then it is dried, milled, and air classified. The Manville proprietary grade, Filter-Cel®, is the one "natural grade" of diatomaceous earth produced from the above processes. To form the larger grades of diatomaceous earth, the Filter-Cel is "calcined" and "flux calcined". Calcining consists of fusing the diatom particles, by heating them to their melting point, producing larger particles. Flux calcining is the same as calcining except a soda-ash flux is added to bond the particles. The soda ash ties up the iron present in the natural grade, giving the product a white appearance. Table 1 lists the various grades of diatomaceous earth manufactured by Manville Corporation, and describes the characteristics of each grade. Table 2 shows the grade equivalents produced by other manufacturers of diatomaceous earth.

The generic term used to describe the diatomaceous earth filtration process is "precoat filtration." Perlite is another filter media made from volcanic ash which has been used also in the filtration of liquids. For this report the term diatomaceous earth filtration will be continued to be used in a generic sense. The term precoat filtration could be confused with the first step of filtration which is called the precoat step.

Applications of Diatomaceous Earth Filtration Process

Diatomaceous earth is widely used as a filtration medium. Applications include the filtration of: waters, pharmaceuticals, dry cleaning solvents, beverages (beer, wine, soft drinks, fruit and vegetable juices, and

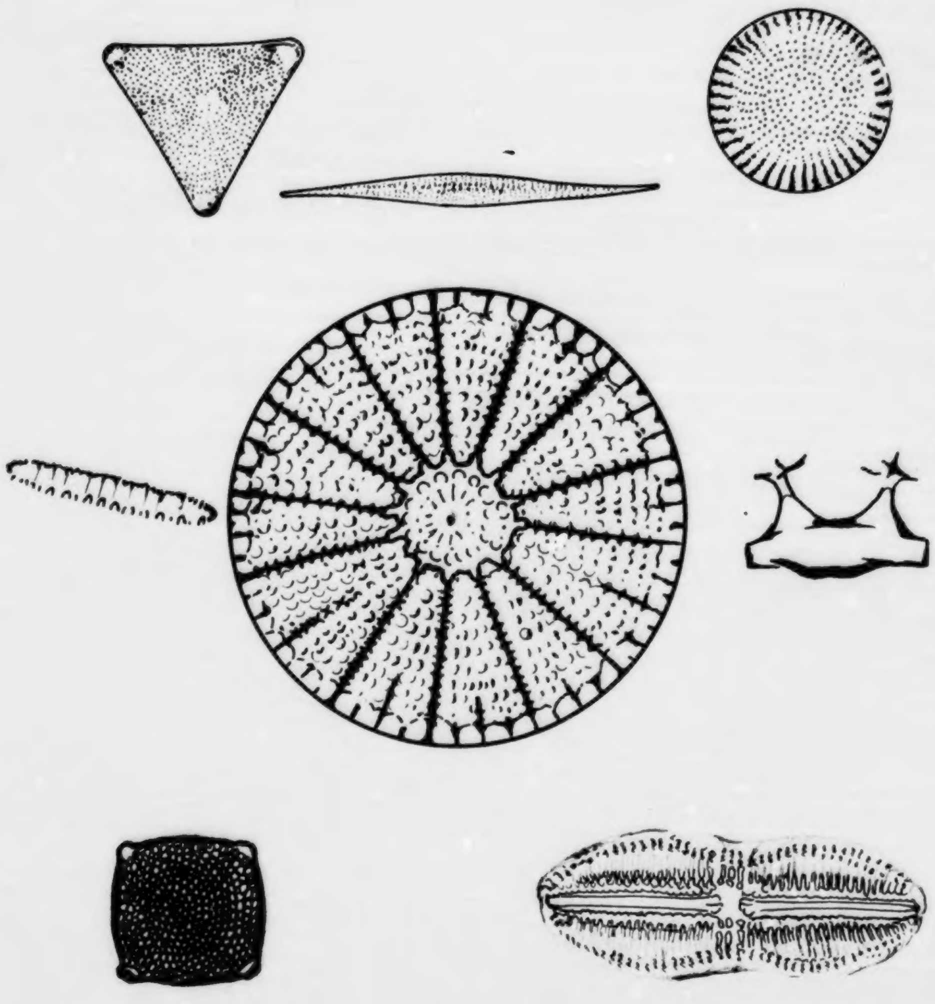


Figure 1. Diatom species typical of the Lompoc, California deposit (after A. B. Cummins, 1974).

Table 1. Typical physical properties of diatomaceous earth grades as provided by Manville Corporation. Adapted from Johns Manville publication entitled, "Johns-Manville Celite filter aids for maximum clarity at lowest cost."

Grades[1]	Color	Median Part. Size (µm)	D_{10} Size (µm)	Median Pore Size (microns)	Approx. ΔP@ 0.68 mm/s with 0.73 kg/m^2 Precoat (cmHg)	Permeability (Darcies)	Density (Kg/m^3) Dry	Wet	% Moisture as Shipped	pH Max.
Filter-Cel	Gray	7.5	1.5	1.5	8.1	0.05	112	256	3.0	7.0
C-505	Pink	-	-	-	5.1	0.07	128	368	1.0	7.0
C-577	Pink	12	2.5	2.5	3.0	0.16	128	288	0.5	7.0
Standard Super-Cel	Pink	14	3.1	3.5	1.8	0.25	128	288	0.5	7.0
C-512	Pink	15	4.3	5.0	1.0	0.53	128	304	0.5	7.0
Hyflo Super-Cel	White	18	5.2	7.0	0.25	1.2	144	288	0.1	10.0
C-501	White	20	8.0	9.0	0.18	1.4	152	288	0.1	10.0
C-503	White	23	10.5	10.0	0.15	2.0	152	288	0.1	10.0
C-535	White	25	11.1	13.0	0.08	3.1	192	304	0.1	10.0
C-545	White	26	12.8	17.0	0.05	4.8	192	304	0.1	10.0
C-550	White				0.04	7.4	288	336	0.1	8.0
C-560	White	106	26.9	22.0	0.01	30.0	312	320	0.1	10.0

[1] All grades are registered trademarks of Johns-Manville.

Table 2. Comparison of precoat filtration media producing same relative clarity of standard sugar solution (adapted from Baumann, 1978).

Relative Flow Rate[1]	Relative Clarity[1]	Manufacturer Eagle-Picher[2]	 Johns-Manville[2]	 Dicalite[2]
100	1000	Celatom FP-2	Filter Cel	215
125	1000	Celatom FW-2	Celite 505	Superaid, UF
200	995	Celatom FP-4	Standard Super-Cel	Speedflow
300	986	Celatom FW-6	Celite 512	Special Speedflow, 231
400	983	Celatom FW-10	--	341
700	970	Celatom FW-12	Hyflo Super Cel	Speedplus, 689 CP-100
800	965	Celatom FW-14	--	375
950	963	Celatom FW-18	Celite 501	CP-5
1000	960	Celatom FW-20	Celite 503	Speedex, 757
1800	948	Celatom FW-40	--	--
2500	940	Celatom FW-50	Celite 535	4200, CP-8
3000	936	Celatom FW-60	Celite 545	4500
4500	930	Celatom FW-70	Celite 550	5000
5500	927	Celatom FW-80	Celite 560	--

[1] Based on bomb filter tests with 60° Brix raw sugar solution, 80°C.

[2] All grades are registered trademarks of the companies indicated.

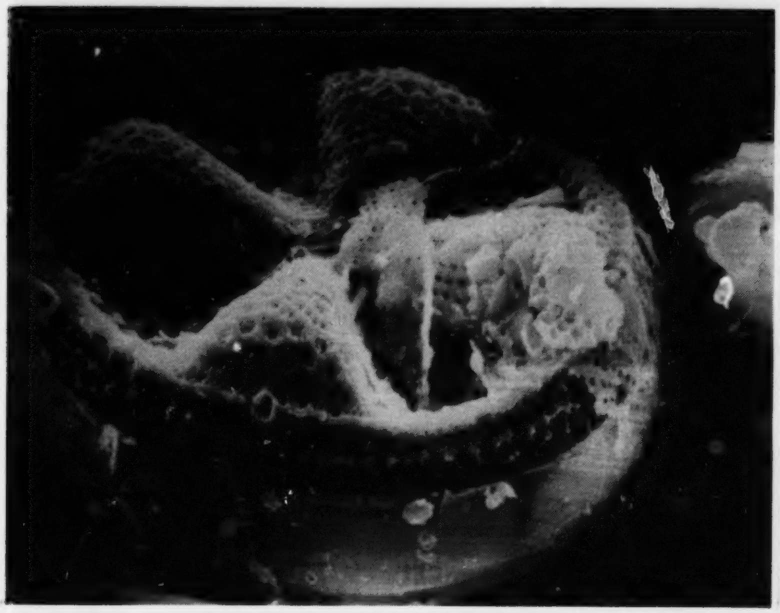


Figure 2. Electronmicrograph 2,000 magnification of one diatom species taken by W. D. Bellamy at Colorado State University.

spirits), raw sugar liquors (cane, beet, and corn), oils (lube, rolling mill, and cutting), jet fuels, organic and inorganic chemicals, varnishes and lacquers, and food products. The water-filtration applications include: industrial filtration of process waters, waste waters, boiler waters, condensate waters, swimming pools, and potable water for the military and municipalities.

History

Diatomaceous earth filtration was used by industry before it found application in water treatment. Diatomaceous earth filters were used in beet sugar plants in Germany in the 1890's, and in 1913 the first large scale application for sugar refining took place. After this the use of diatomaceous earth filtration in industrial applications developed extensively.

The use of diatomaceous earth for potable water filtration began in the 1940's. The United States Army needed a light-weight, portable filter that was capable of removing *Entamoeba histolytica* cysts from water supplied to field troops during World War II. Studies by Black and Spaulding in 1944 showed that diatomaceous earth filtration was effective in the removal of *Entamoeba histolytica* cysts from water supplies. This successful application of diatomaceous earth filtration for producing potable water prompted further studies on the process after the war. E. R. Baumann and others studied diatomaceous earth filtration under Army sponsorship from 1948 to 1955 at the University of Illinois. Baumann continued studies at Iowa State University in the mid 1950's to date (Cummins, 1974).

The first municipal diatomaceous earth filtration water plant was built in Cherry Valley, New York in 1949, after a pilot study in 1947-1948 gained approval for the plant's installation. By 1965, some 85 diatomaceous earth filtration plants had been built in the United States for potable water filtration. And in 1982, design began on a 11 ML/d (3 mgd) ozone/diatomaceous earth pilot filtration plant for New York City. This demonstration plant on the Croton water supply is the initial stage of a planned 984 ML/d (260 mgd) plant.

Process Description

Diatomaceous earth filtration is a three step process which consists of precoating, filtering, and cleaning. The filtration step includes metering of bodyfeed. The flow configurations for these operations are shown in Figure 3 and are discussed below.

Precoat Step

Precoating is the application of diatomaceous earth in a slurry concentration to a support membrane known as a septum. Figure 4 shows the septum in place on the disassembled pilot filtration unit used in this study. The septum used is a wire mesh which has 110 wires x 24 wires to the square inch. The slurry is recycled until the diatomaceous earth in the slurry has bridged on the septum and formed a filter cake 3-5 mm thick. Figure 3a shows the process flow for the precoat step. The recommended amount of precoat is 0.05 to 0.10 Kg/m^2 (0.10 to 0.20 lb/ft^2).

Filtration Step

After completion of the precoat step, the bodyfeed pump is started to allow the slurry sufficient time to mix in the filter vessel. When this occurs, the raw water feed valve is opened to begin the filtration step. Figure 3b shows the flow schematic pattern for the filtration step. The raw water is pumped through the filter at .34 to 3.4 mm/s depending on the application and grade used. Suspended particulates are removed as the water is pumped through the filter cake. The filtrate leaves the filter vessel through a central manifold. This effluent is then collected for clear water storage. For production of potable water, disinfection will accompany clear water storage.

During the filtering step as shown in Figure 3b, it is necessary to add a continuous feed of concentrated diatomaceous earth slurry, called the "bodyfeed", to the filter. This continuous addition of diatomaceous earth helps maintain a constant permeability by preventing the buildup of particles on the media surface. Instead the bodyfeed continuously adds to the filter media suspending the removed particulates within the filter cake. This creates a homogeneous incompressible filter cake. Figure 5 shows a cross section of the filter cake as it forms on the septum during precoat and filtration.

The concentration of bodyfeed that should be added to the filter is dependent on the raw water characteristics. The proper concentration for

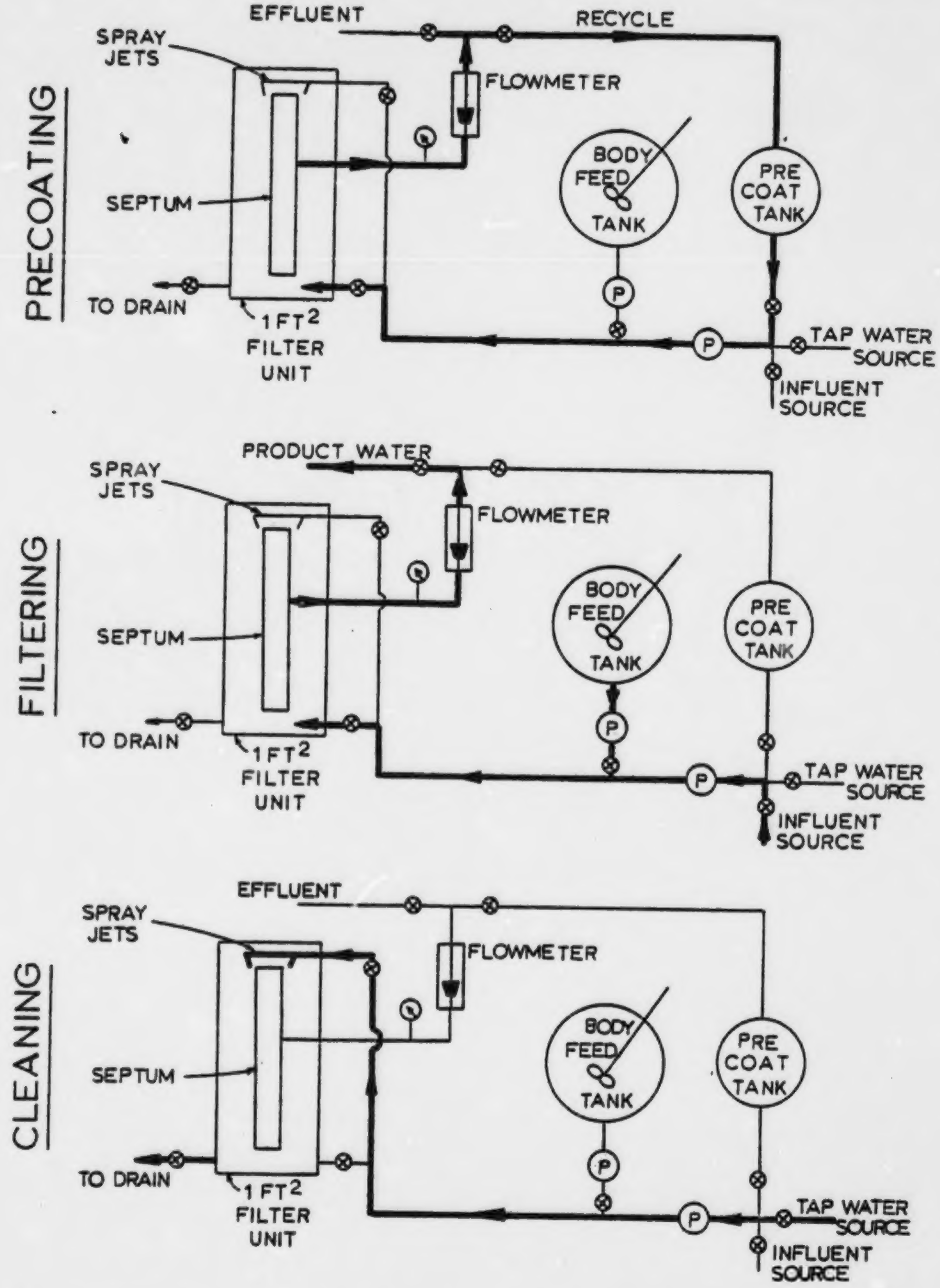

PRECOATING
EFFLUENT
RECYCLE
SPRAY JETS
FLOWMETER
BODY FEED TANK
PRE COAT TANK
SEPTUM
TO DRAIN
1 FT^2 FILTER UNIT
P
TAP WATER SOURCE
INFLUENT SOURCE
FILTERING
PRODUCT WATER
SPRAY JETS
FLOWMETER
BODY FEED TANK
PRE COAT TANK
SEPTUM
TO DRAIN
1 FT^2 FILTER UNIT
P
TAP WATER SOURCE
INFLUENT SOURCE
CLEANING
EFFLUENT
SPRAY JETS
FLOWMETER
BODY FEED TANK
PRE COAT TANK
SEPTUM
TO DRAIN
1 FT^2 FILTER UNIT
P
TAP WATER SOURCE
INFLUENT SOURCE

Figure 3. Flow schematics of the diatomaceous earth filtration steps: a) precoating, b) filtering, and c) cleaning.

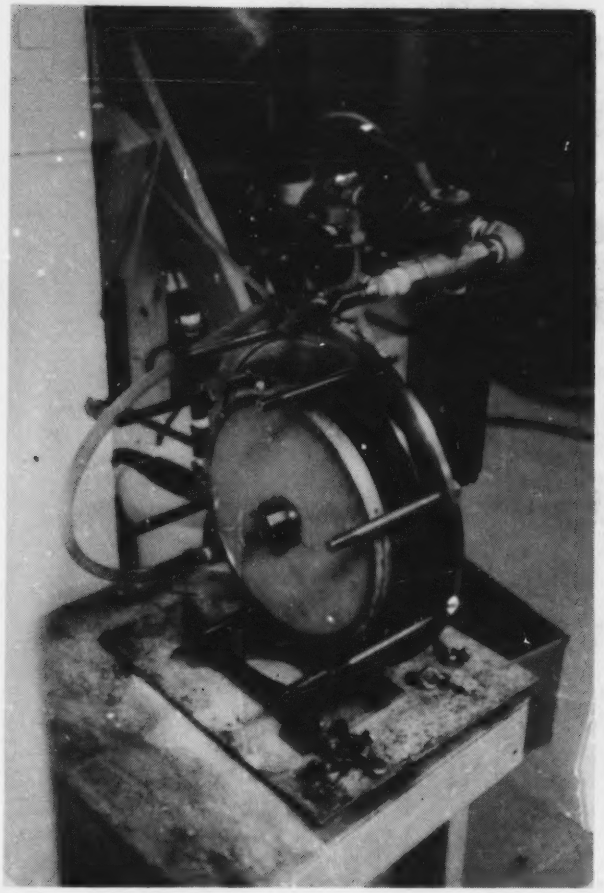


Figure 4. Support septum in place on disassembled filter unit.

any given water should produce a linear relationship when headloss versus filtration time is plotted on arithmetic graph paper. Figure 6 shows the hypothetical headloss versus time curves for inadequate, adequate, and above adequate bodyfeed concentrations.

Cleaning Step

The filtration process is discontinued when the headloss reaches a predetermined value. This is approximately 70 kPa (10 psi) for vacuum filters and 210 kPa (30 psi) for pressure filters. Figure 3c shows the flow schematic used in the cleaning step. The spent media must be removed from the septum in order to apply the fresh precoat. The three most widely used techniques for removing the filter cake include backwashing, spray jet washing, and sluicing; an additional technique not commonly used is the "air bump". The first three techniques are different hydraulic means to wash the diatomaceous earth from the septum. The "air bump" is a shock applied to the system, causing the cake to fall off. The pilot filter used in this study employed spray jets, with varying flow rate.

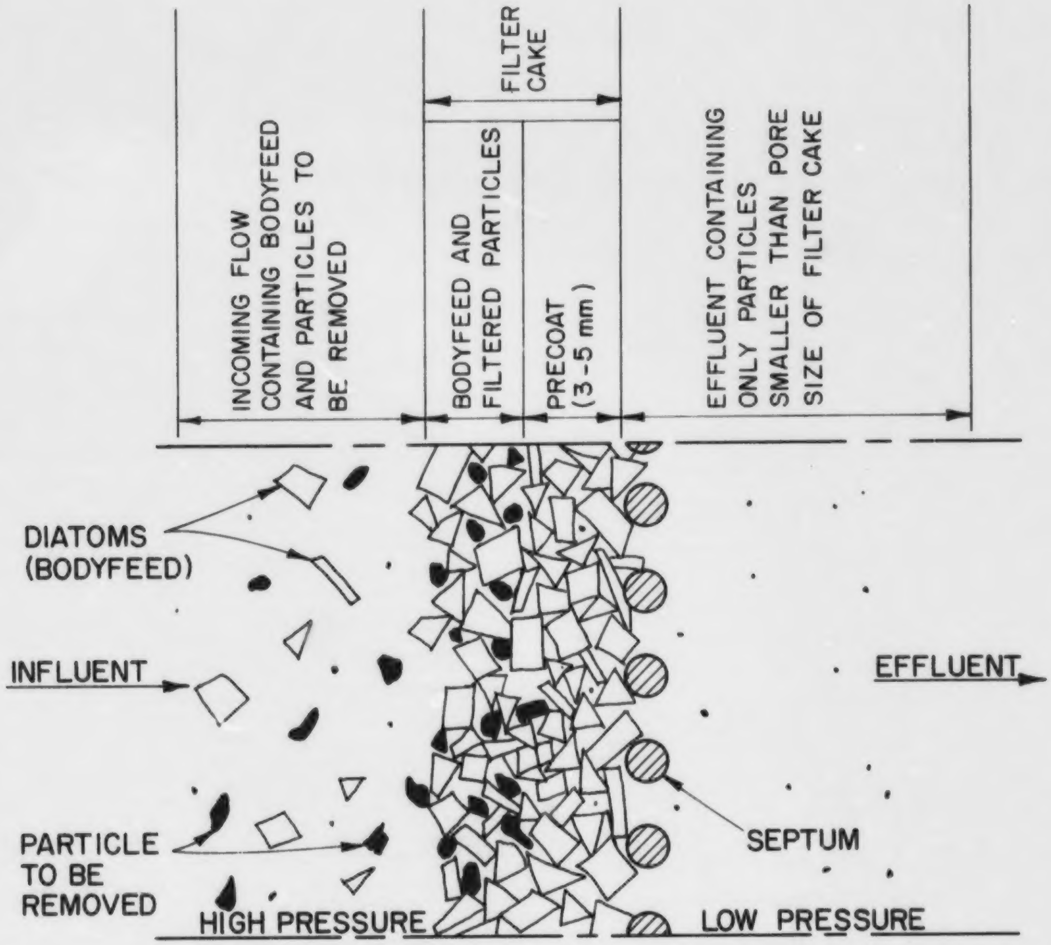

FILTER CAKE
INCOMING FLOW CONTAINING BODYFEED AND PARTICLES TO BE REMOVED
BODYFEED AND FILTERED PARTICLES
PRECOAT (3-5 mm)
EFFLUENT CONTAINING ONLY PARTICLES SMALLER THAN PORE SIZE OF FILTER CAKE
DIATOMS (BODYFEED)
INFLUENT
EFFLUENT
SEPTUM
PARTICLE TO BE REMOVED
HIGH PRESSURE
LOW PRESSURE

Figure 5. Cross section of a diatomaceous earth filter, showing filter cake development, adapted from "Celite filter aids for maximum clarity at lowest cost, "Johns-Manville brochure.

Research Studies

Water filtration applications using diatomaceous earth began in 1942 when A. B. Cummins (1942) and A. S. Elsenbast and D. C. Morris (1942) in separate work studied the clarification efficiency of diatomaceous earth. These early studies showed that the flow characteristics of diatomaceous earth are affected by: 1) the range of particle sizes found in a given grade of diatomaceous earth (Elsenbast and Moore, 1942), and 2) the shape of the particles in a given grade (Cummins, 1942).

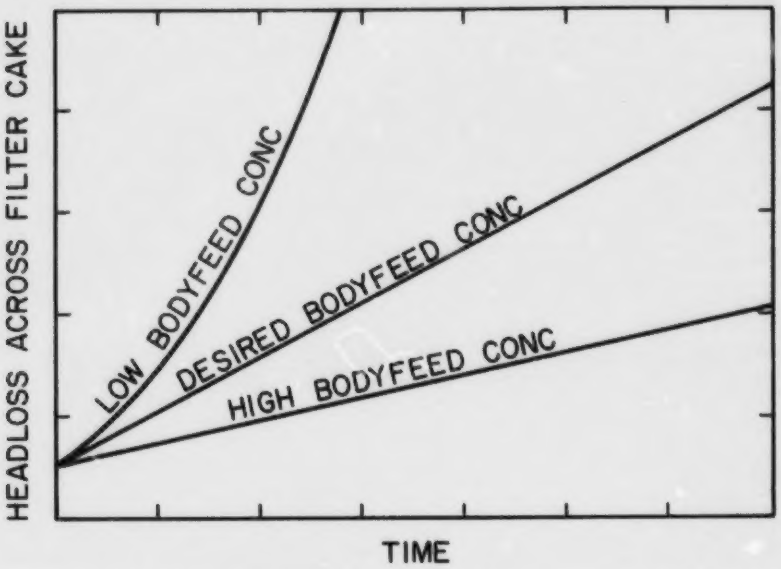


Figure 6. Headloss across filter cake, plotted against time showing the affect of various concentrations of bodyfeed slurry. Adapted from R. W. McIndoe, 1969.

The use of diatomaceous earth for potable water filtration began with a study sponsored by the United States Army. In 1944, H. H. Black and C. H. Spaulding (1944) developed a light weight, portable diatomaceous earth filtration system for military field use, capable of filtering Entamoeba histolytica cysts from water supplies. The authors acknowledged that this system was a "sound and workable" technique of water filtration for field troops, but required more development for widespread filtration applications. This study marked the beginning of a diatomaceous earth research and development program for its application to water treatment.

Baumann and Babbit began researching the basic principles of diatomaceous earth filtration in 1947 (Baumann, 1965) for the U.S. Army Engineer Research and Development Laboratories (ERDL). Their studies along with Maloney, Martin, Zaghloul, Petrica, Wah, and Zobel for the ERDL from 1947-1955 included research of septum effects, bodyfeed effects, design factors, operating conditions, various filter designs, removal of Entamoeba histolytica cysts, and the role of coagulation.

In the early 1960's there were numerous investigations of the theory and the practice of diatomaceous earth filtration. In 1962, LaFrenz and Baumann (1962) began studies into the optimization of bodyfeed concentration, filtration rate, and terminal headloss. Also, in 1962, Baumann, Cleasby, and LaFrenz (1962) established a theory of diatomaceous earth filtration which included various headloss equations for the filtration process. G. R. Bell (1962) determined design criteria for filters. His suggested guidelines for filter vessels included hydraulic velocities, septum considerations, adequacy of filter cleaning, precoating technique, and principles of continuous bodyfeed addition. Bell did additional studies in the early 1960's investigating enhanced particulate removal by coagulant coating of diatomaceous earth, comparisons of diatomaceous earth filtration to rapid sand filtration, and bacteria removal efficiencies of various diatomaceous earth grades.

In 1962, Van der Velde and Crumley (1962), Coogan (1962), and Moore (1962) explained experiences with municipal diatomaceous earth filtration installations in Michigan, Massachusetts, and New York, respectively. The general performance, operational experience, and cost of operations were discussed. Coogan's study also discussed the success of using diatomaceous earth filtration for iron and manganese removal.

During the 1960's, diatomaceous earth studies were broadened to include the process variation of coagulant coating the diatomaceous earth to enhance particle removal through adsorption. Burns, Baumann, and Oulman (1962) studied this process variation and found that: 1) particle removal was dependent on transport and attachment mechanisms, 2) that the amount of coagulant required was dependent upon the surface area of the diatomaceous earth to be coated, i.e. grade, and 3) that the coated filter media works best for polishing waters rather than for gross particle removal. At about the same time Dillingham and Baumann (1964) determined the hydraulic and particle characteristics of various grades of diatomaceous earth. Oulman and Baumann (1964) studied the zeta potential of various grades of diatomaceous earth. This work continued in the 1970's with Oulman and Baumann's (1971) studies of several polyelectrolyte coatings. They studied nine different coagulants, polyelectrolytes, and natural polymers to determine the most effective in terms of reversing the zeta potential of the filter medium without effecting filter cake resistance. They also determined the effective dosages of these coagulants. In 1979, Welday and Baumann studied eight polymers. The polymers were characterized by investigating the relationships between the zeta potential of the polymer-coated particles, their filtration resistance, and the water pH. They found that the filtration resistance of the filter cake can be decreased by adding small amounts of cationic polymers and that the pH of the water effects the zeta potential of some but not all polymers.

Studies also were conducted in the late 1960's to determine a theory and an optima for the design and operation of diatomaceous earth filtration systems. In 1966, Dillingham, Cleasby, and Baumann (1966) developed mathematical models to optimize variables that affect costs. This included a computer program for optimization of plant operations (POPO). In 1967, Dillingham, Cleasby, and Baumann (1967) further modified filtration equations and filter cake resistance prediction equations for use in optimizing diatomaceous earth filtration plant design. The most recent work on diatomaceous earth filtration equations was done in 1982. Stephenson and Baumann (1982) modified filtration equations for flat and cylindrical septa. They determined that the type of septum has a significant effect on the pressure drop generated for a given time of filtration, and that small diameter cylindrical septa result in a more efficient use of energy.

In 1965, an AWWA Task Group chaired by Baumann (1965) studied municipal applications of diatomaceous earth filtration. They surveyed 88 plants across the United States and found that diatomaceous earth filtration systems are successful if designed, constructed, and operated properly. They also suggest that further studies should be done to determine a standard of design and operation for these systems.

After the study by the AWWA Task Group, more information on the performance and design of municipal installations was reported. In 1967, Syrotynski (1967) evaluated the performance of diatomaceous earth filtration installations in New York state. He used data on turbidity, total microscopic count, color, and headloss to evaluate the performance of these plants. In 1969, Lawrence (1969) studied the Lompoc, California lime-soda ash softening plant and the role that the diatomaceous earth filtration system had in its success. After initial equipment difficulties, the plant performed well beyond the design expectations and requirements.

The most recent study on diatomaceous earth filtration installations was done by Bryant and Brailey (1980). During the late 1970's they completed pilot studies on various systems for treating New York City's Croton water supply. By 1980, it was decided that an 11 ML/d (3 mgd) ozone-diatomaceous earth filtration pilot plant would be constructed for further studies. If this phase of the study is successful, a 984 ML/d (260 mgd) ozone-diatomaceous earth filtration system will be constructed. If constructed this will be the first large capacity diatomaceous earth filter installation and the first plant recovering and recycling of diatomaceous earth material.

In addition to the studies in the early 1960's on the removal of particulates, bacteria, iron, and manganese by diatomaceous earth filtration, the removal of viruses, and asbestiform fibers, have been investigated. In 1974, Brown, Malina, and Moore studied virus removal by diatomaceous earth filtration. They found that without coagulant coatings greater than 90% removal occurred and when the diatomaceous earth was coated with ferric hydrate or polyelectrolytes greater than 98% removal occurred. They also determined that changing filtration parameters, flow rate, and grade of diatomaceous earth did not significantly affect the removal of viruses.

In 1974, two pilot plants were operated at Duluth, Minnesota to study the removal of asbestiform fibers from Lake Superior water. Baumann (1975) studied the results of 228 pilot plant test runs to determine the removal of asbestiform fibers and the optimization of plant design for asbestiform fiber removal. He found that alum coated Hyflo Super-Cel and alum coated C-512, both produced by Manville Corporation, were most effective in overall finished water quality and that vacuum diatomaceous earth filters are more expensive to operate and do not work as well as pressure filters in filtering raw waters with a high turbidity.

The most recent studies began in 1977 and 1978 when Logsdon (1981) and DeWalle (1984) studied the removal of Giardia cysts and cyst models. DeWalle found, using Giardia lamblia cysts, that removal was greater than

99% in all cases. He also determined that a precoat thickness of 1.0 Kg/m^2 (0.20 lbs/ft^2) was most effective in _Giardia_ cyst removal and that the precoat thickness was more important than grade size in _Giardia_ cyst removal. This confirmed the work of Logsdon.

SECTION 2

SUMMARY AND CONCLUSIONS

Scope of Project

The diatomaceous earth filtration process was challenged with Giardia cysts, total coliform bacteria, standard plate count bacteria, particles, and turbidity, over a wide range of experimental conditions in some 56 test runs. The influences of operating conditions were examined, including: grade of diatomaceous earth, hydraulic loading rate, concentration, run time, temperature, and alum coating.

Results from the experimental work are summarized in the paragraphs following. Conclusions are developed also.

Giardia Cyst Removal

Removals of Giardia cysts were greater than 99.9 percent in 29 out of 30 test runs in which Giardia cysts were used. The exception occurred when the filter was challenged with a raw water suspension containing 33,600 cysts/liter. The water treatment grade of diatomaceous earth, C-545, was used in 13 of the test runs, with hydraulic loading rates of 2.44, 4.88, and 9.76 m/hr, and temperatures of 5° and 13°C. Both lake water (NTU 3.5 to 9.5) and clear river waters (0.55 and 3.7 NTU) were used as raw water sources. Influent raw water Giardia cyst concentrations varied from 100 to 10,000 cysts/L (and one of 36,000 cysts/L). From these results, it seems reasonable to assert that diatomaceous earth filtration will remove Giardia cysts under virtually all expected ambient conditions and all usual operationing conditions. These results are consistent with the findings of Logsdon, et al. (1981) using Giardia muris cysts and radioactive beads as cyst models.

Other Substances

Removals of other substances, e.g. particles, total coliform bacteria, standard plate count bacteria, and turbidity, were influenced by operating conditions. For the C-545 grade, particle removals for the 6.35 to 12.67 micrometer size range were at 96 percent for all hydraulic loading rates. Total coliform bacteria removals ranged nominally from 25 to 35 percent, while total plate count bacteria removals ranged from 45 to 60 percent. Turbidity removals using water from Horsetooth Reservoir were only 13 to 16 percent. The influences of operating conditions are outlined as follows.

Grade of Diatomaceous Earth

Median particle sizes of diatomaceous earth grades range from 7.5 micrometers for Filter-Cel to 26 micrometers for C-545. Removals of total coliform bacteria, standard plate count bacteria, and turbidity are strongly influenced by grade. Removals were high, e.g. 99.9 percent for bacteria and 98 percent for turbidity for tests using Filter-Cel, but were much less for C-545, e.g. 30 percent for bacteria and 15 percent for turbidity. The removal mechanism seems to be straining and so as the pore size increases with the larger grades, fewer particles are retained. Other waters may be more amenable to more effective turbidity removal using the C-545 grade. Pilot plant testing is imperative to determine this. The C-545 grade is, of course, favored, due to a lower rate of headloss increase.

Hydraulic Loading Rate

Tests runs were made mostly at the hydraulic loading rate of 2.44 m/hr, which is usual for practice. Some test runs were done at 4.88 and 9.76 m/hr to ascertain the effect of hydraulic loading rate. The data seem to show a declining percent removal for some parameters as hydraulic loading rate increases, but the trends are not unequivocally supported by the data points. The trend with particles is essentially flat, and so is the turbidity trend. Removals of coliform bacteria and total plate count bacteria show the sharpest declines. Removal of Giardia cysts is not affected by hydraulic loading rate. From this it would seem reasonable to assert that hydraulic loading rate is not a critical parameter in its influence on removal effectiveness. Rather, selection of a design hydraulic loading rate should be based upon more practical considerations, such as its effect on length of run. Reductions in bacteria removal effectiveness due to using higher rates can be compensated in the disinfection process.

Temperature

Tests at 5° and 13°C involved bacteria concentration changes which obscured any effect of temperature. There was, however, a definity relationship between lower temperature and poorer turbidity removal, i.e. 13 percent removal at 13°C and 5 percent removal at 5°C.

Concentration

Tests run at different concentrations of total coliform bacteria showed a decline in percent removals as concentrations increased from 50 org/100 ml to 30,000/100 ml. The effect was least for C-512, the grade having the smallest median particle size, and most for C-545. Practically this result suggests that if the water is highly polluted a smaller grade should be used, but for the nominally polluted waters usually encountered in the Rocky Mountain Region, e.g. with 1,000 org/100 ml, the C-545 grade should be suitable, if disinfection is effective and if there are no pollution hazards.

Length of Run

As run time increases, e.g. from 30 min to 330 min., removal effectiveness for total coliform bacteria will decline modestly. The effect is most for the coarser grades of diatomaceous earth and almost negligible for the finer grades. Practically it is a phenomenon of which the operator should be aware, and pilot testing should be sufficient to ascertain its importance for the conditions at hand, prior to design.

Alum-Coated Diatomaceous Earth

Alum coating on the pre-coat and body feed causes dramatic improvement of percent removals for all parameters, particularly bacteria and turbidity. Bacteria removals can be improved from 30-40 percent range to >99 percent if alum coating is used. Turbidity removals can be improved from the 15 percent range to near 98 percent. The alum could be used routinely, or, if the water is usually treatable, only during episodes of difficult treatability. It may be considered in lieu of smaller grades. The effectiveness increases as the alum-diatomaceous earth ratio (gms alum/gm diatomaceous earth) increases, up to an optimum concentration. Pilot testing is required to establish this. About 0.05 gm alum/gm diatomaceous earth was satisfactory for Horsetooth Reservoir water, using a pre-coat of 1 kg/m^2 and bodyfeed of 25 mg/l. The rate of headloss increase will become larger with the use of alum coating. Our tests showed the rate of headloss increase was 3 to 17 cm Hg/hr compared with plain diatomaceous earth, which was 0.01 to 2.5 cm Hg/hr.

Water

All of the laboratory testing was performed using raw water from Horsetooth Reservoir. The turbidity ranged from 3.5 to 9.5 NTU during the testing which covered the summer, fall, and winter seasons. The seasonal changes had no influence on results. Also when the pilot plant was moved to two different river locations for tests, with 3.5 NTU and 0.5 NTU turbidities, respectively, the results obtained were consistent with those obtained during laboratory testing. This is not to assert that the water has no influence, but changes imposed did not have a great influence upon our results.

SECTION 3

INVESTIGATION

This study focused upon removal of Giardia lamblia cysts from water supplies by diatomaceous earth filtration. In addition we examined removal of total coliform bacteria, standard plate count bacteria, turbidity, and particles as a function of operating conditions. This section describes the reasons for the study, its objectives, its scope, and its significance. Since the major interest of the investigation is removal of the Giardia lamblia cysts, the prevalence of the disease giardiasis is reviewed and the characteristcs of the organism are outlined.

Outline of Research

Purpose

The purpose of this study is to ascertain the effectiveness of the diatomaceous earth filtration process for removal of Giardia lamblia cysts from surface water supplies, and the role of operating conditions. This information may serve as the basis for development of process design and operating guidelines, supplementing what is known already.

Objectives

The objective was to determine the effectiveness of diatomaceous earth filtration for removal of Giardia lamblia cysts, turbidity, total coliform bacteria, standard plate count bacteria, and particles as a function of different operating conditions. The operating conditions include: grade of diatomaceous earth, hydraulic loading rate, temperature, headloss, influent concentration of Giardia lamblia cysts, influent concentration of bacteria, and run time. Also of interest is the effect of alum coated diatomaceous earth in filtration of turbidity, total coliform bacteria, and standard plate count bacteria.

Scope

The study was a laboratory investigation in which operating conditions were maintained constant while only one variable was changed to determine the respective functional dependence of the dependent variables. Limited field testing was done to corroborate laboratory results. Some operating conditions, e.g. precoat thickness and bodyfeed concentrations, were recommended values from previous studies.

Significance

This study is intended to define operating conditions for removal of viable Giardia lamblia cysts by diatomaceous earth filtration. From this information design and operating guidelines may be developed which will supplement existing knowledge. The research also provides additional familiarity with the performance characteristics of diatomaceous earth filtration which can be useful to regulatory agencies and to others having an interest in the process.

Gardia Lamblia

Giardiasis

Public water supplies have been implicated in numerous outbreaks of giardiasis in several areas of the United States. The increased reporting of giardiasis is due in part to the efforts of public health personnel in identifying cases; until recent years symptoms of giardiasis were ascribed to the general category, gastroenteritis. The first documented waterborne outbreak of giardiasis occurred at Aspen, Colorado, during the winter of 1965-1966. Greater than 11 percent of the 1,094 vacationing skiers surveyed over a two-month period developed giardiasis. The town's water supply was treated with chlorine only.

The largest outbreak of giardiasis and the first where a Giardia lamblia cyst was recovered from a municipal water supply occurred in Rome, New York, during November 1974 to June 1975. A total of 350 residents had laboratory-confirmed giardiasis and an estimated 5,300 others may have been symptomatic. Again, chlorine was the only form of water treatment.

Outbreaks in Camas, Washington, in 1976 and Berlin, New Hampshire, in 1977 were the first cases of Giardia cysts being found in a filtered water supply. Subsequent reports from Estes Park, Colorado, (1979) and Vail, Colorado (1980) reinforced the growing seriousness of the problem. These cases and others aroused the widespread interest of public health officials and prompted the Environmental Protection Agency to sponsor research.

Protozoan Giardia lamblia

The protozoan Giardia lamblia and the associated disease, giardiasis, are described in the proceedings of a symposium, edited by Jakubowski and Hoff (1979). The protozoan Giardia lamblia was first observed by Antony van Leeuwenhoek in 1681 (Dobel, 1932). The genus was named in 1882 by Joseph Kunstler. The species Giardia lamblia was established in 1915 by Charles Wardell Stiles, and prior to this was synonymously known as Giardia intestinalis, duodenalis, and enterica.

The organism has two life stages: a reproductive trophozoite stage and a dormant cyst stage. These two life stages are shown in Figure 7.

The trophozoite, shown in Figure 7a, is pear-shaped, with a broad anterior and a blunt, pointed posterior. The dorsal side is convex, while the ventral side contains a sucking disc and is concave. Its dimensions are 9-21 μm long by 5-15 μm wide and 2-4 μm thick. The trophozoite also is bilaterally symmetrical, has two nuclei, and eight flagella.

The cyst, shown in Figure 7b, is ovoid to ellipsoidal in shape with a translucent cyst wall approximately 0.3 μm thick. Its dimensions are 8-12 μm long by 7-10 μm wide. Newly formed cysts have two nuclei while mature cysts usually have 4 nuclei. It is uncertain when division and doubling of organelles occurs, but during excystation two trophozoites emerge.

Table 3 shows the different names used to identify Giardia cysts from different hosts. It is believed that the species in group 1 are the same and therefore may be cross-transmitted between hosts of different animal species. Hibler (Davies et al., 1983) has reported self infection using Giardia cysts obtained from dogs. The characteristics of Giardia lamblia cysts and Giardia canis are identical. There is every reason to believe that Giardia lamblia and the so-called Giardia canis are the same organism. This is corroborated in a different manner by Hewlett, et al. (1982) who established that Giardia cysts from infected persons can infect dogs.

Infection is caused by ingestion of between one and ten cysts (Rendtorff, 1954). Giardiasis symptoms will appear anywhere from two to thirty-five days after ingestion with one to two weeks as the most common incubation period. The cyst is the only life stage that is infectious. It survives digestive processes and harbors in the small intestine. Once exposed to Giardia lamblia the host is a lifetime carrier. Presently, drugs with harmful side effects will cure the symptoms but the disease can recur, especially during stressful periods. Symptoms include: flatulence, foul stools, cramps, distention, anorexia, nausea, weight loss, belching, heartburn, headache, constipation, vomitting, fever, chills, and fatigue.

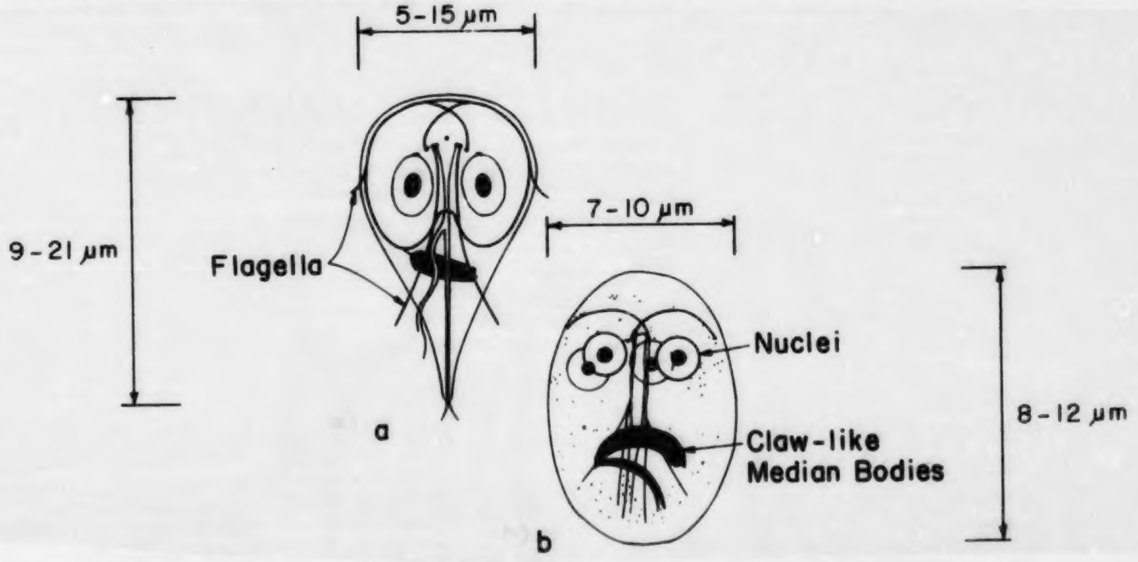


Figure 7. Sketches of a) trophozoite, and b) cyst stages of Giardia lamblia (Jackubowski and Hoff, 1979).

Table 3. Different species names given to *Giardia* found in specific hosts (Jakubowski, 1979).

Different Species Identification	Host Originated From
1. Claw-like Median Bodies	
Giardia lamblia	Man
Giardia intestinalis	Man
Giardia enterica	Man
Giardia canis	Dog
Giardia cati	Cat
Giardia bovis	Ox
Giardia duodenalis	Rabbit
Giardia simoni[1]	Rat, Mouse
2. Rounded Median Bodies	
Giardia muris[1]	House Mouse, Rat, Hamster

[1] Cross-transmittance of these species has not been demonstrated.

SECTION 4

EXPERIMENTATION

The experimental program, and the experimental procedures are described in the paragraphs following. This includes descriptions of the plan of experimentation, the pilot plant, testing protocol, sampling and measurement techniques, data processing procedures, and quality control measures.

Experimental Program

The general strategy of the experimental program was to evaluate the removal effectiveness of diatomaceous earth filtration on the dependent variables, listed in Table 4, as a function of the independent variables, i.e., the operating conditions, listed in Table 5. Table 5 includes the testing ranges of the independent variables.

The effect of each independent variable on treatment efficiency, i.e. the dependent variables, was determined by conducting a set of test runs for each independent variable. The set of test runs consisted of changing the independent variable to a new value for each test run in a set and then holding all of the independent variables constant during the test run. Any change in treatment efficiency could then be correlated to the independent variable which was changed during a set of test runs.

Testing program

Figure 8 shows in a three-dimensional matrix format the concept of the testing sequence comprising the experimental program for evaluation of *Giardia* cyst removal effectiveness. The matrix shows that the sequence of testing is a logical succession of imposing or relaxing test conditions one at a time, as described above. Evaluation of the other dependent variables listed in Table 4 was done simultaneously with the *Giardia* cyst evaluation.

Pilot Plant Description

A laboratory scale pilot plant was utilized in this research to evaluate the diatomaceous earth filtration process. The filtration unit, obtained from Manville Corporation, is shown in Figure 9. It is an enclosed pressure housing with a one square foot wire-mesh septum inside. Figure 10 shows the filter unit with the appurtenances used by Manville Corporation in routine testing.

Table 4. Dependent variables measured in testing diatomaceous earth filtration performance.

1. *Giardia lamblia* cysts
2. Total coliform bacteria
3. Standard plate count bacteria
4. Turbidity
5. Particle
6. Headloss

Table 5. Independent variables and ranges used in diatomaceous earth filtration testing program.

Operating Conditions	Range
Grade of diatomaceous earth	C-545, C535, C503, Hyflo Super-Cel, C-512, Standard Super-Cel, Filter-Cel
Runtime (length of filtration)	2, 5, and 16.0 hours
Headloss	0-100 feet of water
Hydraulic loading rate	2.44, 4.88, and 9.76 m/hr
Temperature	5°C, 15°C, ambient (11-19°C)
Influent *Giardia lamblia* cyst conc.	100-33,600 cysts/liter
Influent coliform bacteria conc.	3,800-380,000 coliform/100 ml
Alum diatomaceous earth ratio	0-0.08 gm alum/gm diatom. earth
Precoat thickness	0.093 Kg/m^2 (0.20 lb/ft^2)[2]
Bodyfeed concentration	25-400 mg/l[2]
Bodyfeed to turbidity ratio	2.5-44.0[2]

[1] The precoat thickness was held constant for all tests.

[2] The bodyfeed concentration was only changed to accommodate proper operation. No treatment evaluations were conducted with this parameter.

Filter set-up

The pilot plant, shown in Figure 10, is a modification of the Manville Corporation design, with additional appurtances to reduce pressure surges, improve flow control, and add pressure measurement accuracy. Figure 11 is a flow schematic which corresponds to the set-up shown in Figure 10. Table 6 lists the pilot plant equipment and appurtenances, their specifications, and their purposes.

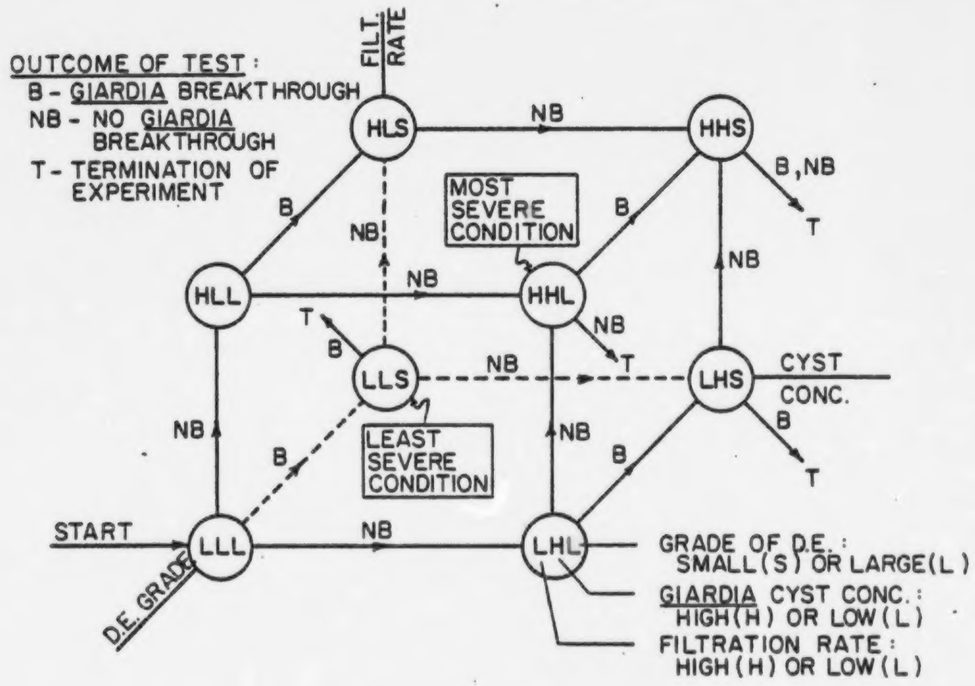

OUTCOME OF TEST:
B - GIARDIA BREAKTHROUGH
NB - NO GIARDIA BREAKTHROUGH
T - TERMINATION OF EXPERIMENT
FILT. RATE
HLS
HHS
HLL
HHL
LLS
LHS
LLL
LHL
MOST SEVERE CONDITION
LEAST SEVERE CONDITION
NB
B
B,NB
T
CYST CONC.
START
D.E. GRADE
GRADE OF D.E.: SMALL (S) OR LARGE (L)
GIARDIA CYST CONC.: HIGH (H) OR LOW (L)
FILTRATION RATE: HIGH (H) OR LOW (L)

Figure 8. Matrix of testing space for diatomaceous earth filtration experiments, temperature constant.

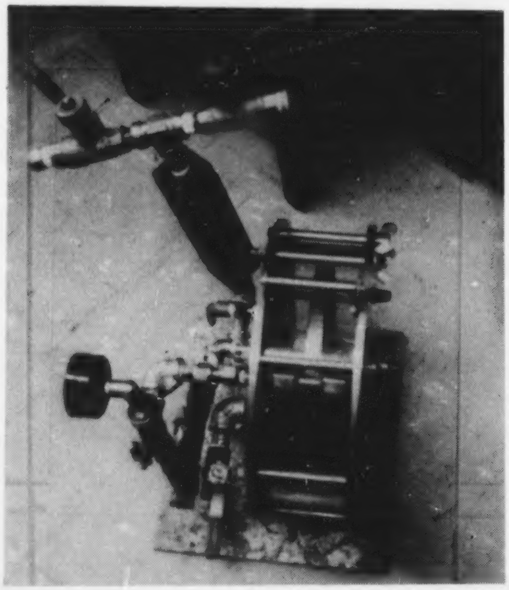


Figure 9. The one square foot diatomaceous earth pilot filter supplied by Manville Corporation.

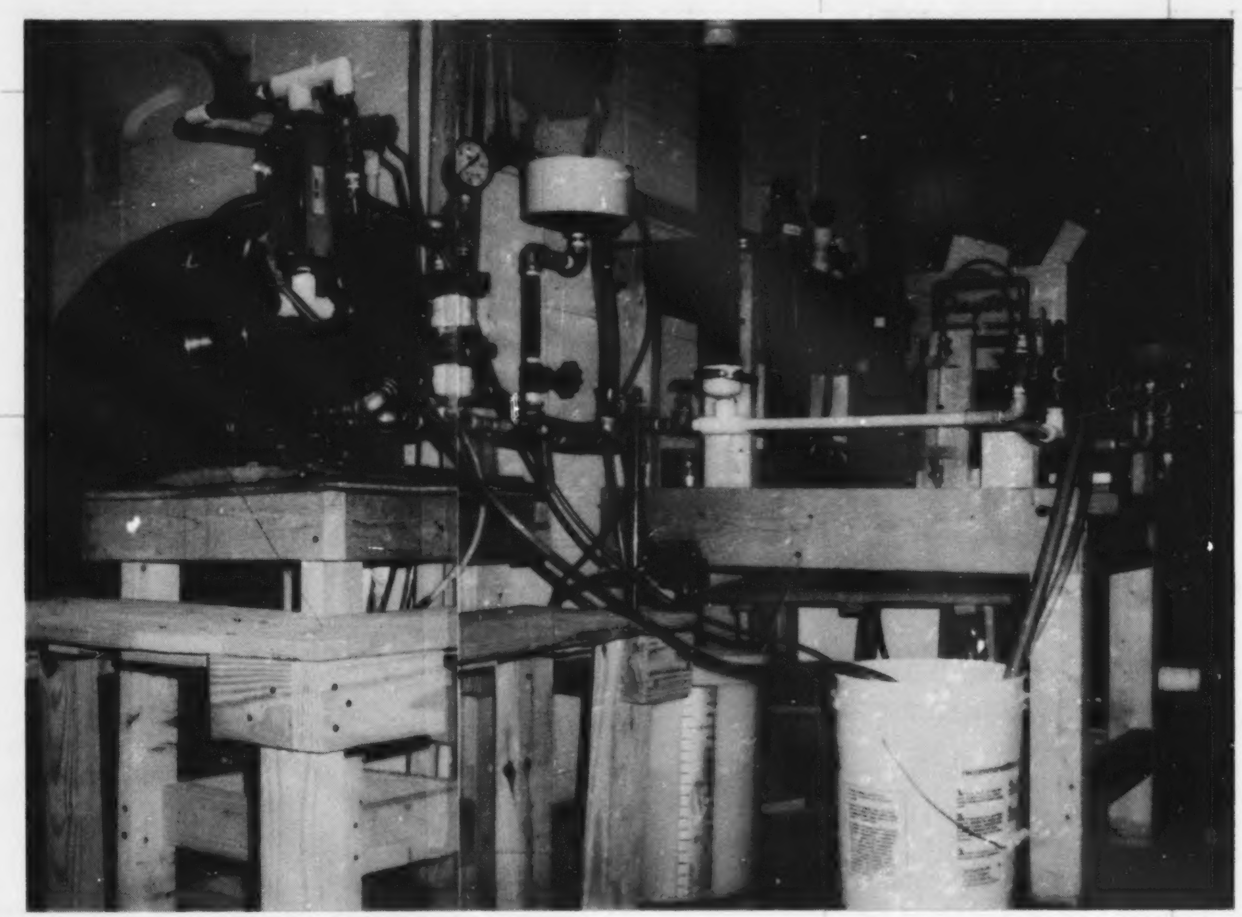


Figure 10. The one square foot diatomaceous earth filtration pilot plant with appurtenances.

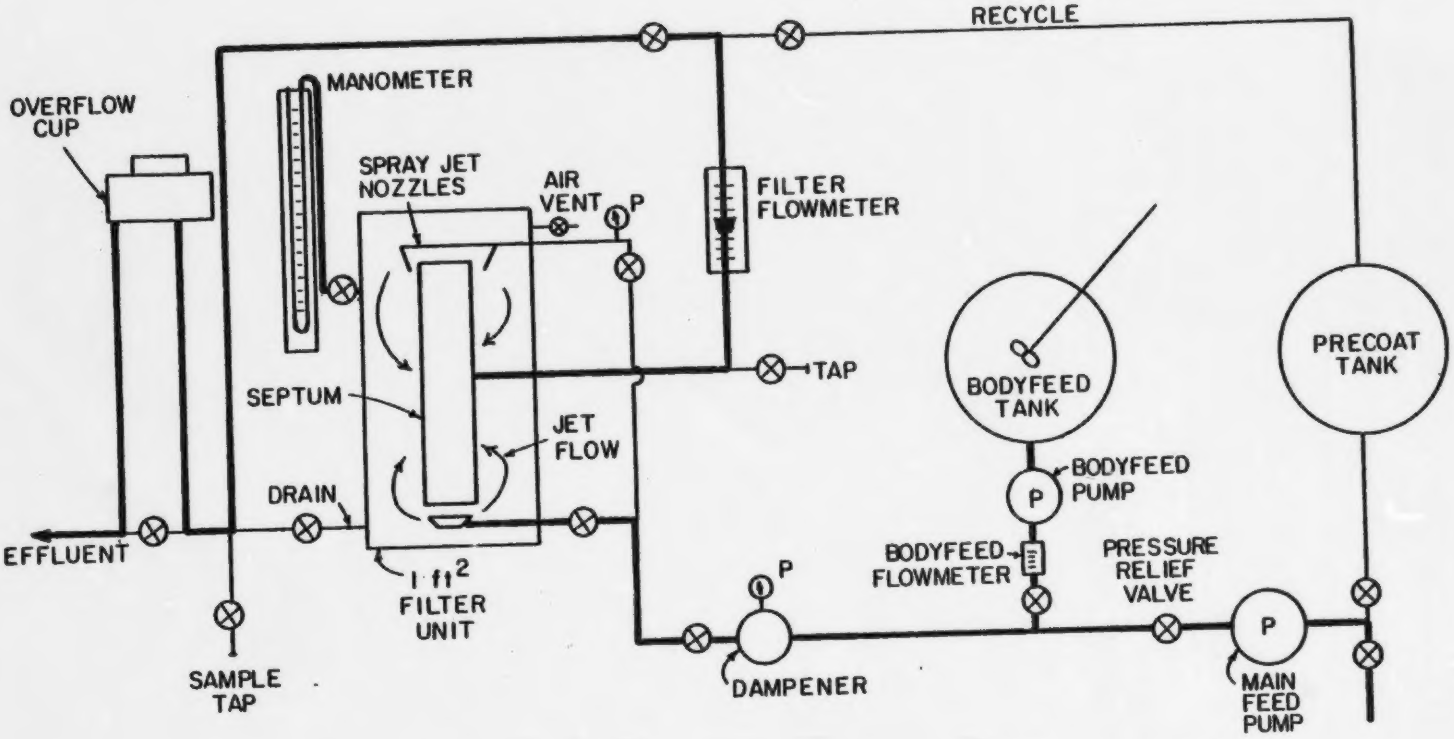

RECYCLE
OVERFLOW CUP
MANOMETER
SPRAY JET NOZZLES
AIR VENT
P
FILTER FLOWMETER
TAP
SEPTUM
JET FLOW
DRAIN
EFFLUENT
1 ft²
FILTER UNIT
SAMPLE TAP
P
DAMPENER
BODYFEED TANK
P
BODYFEED PUMP
BODYFEED FLOWMETER
PRESSURE RELIEF VALVE
P
MAIN FEED PUMP
PRECOAT TANK

Figure 11. Layout of diatomaceous earth filtration pilot plant.

Table 6. List of equipment and appurtenances used in the operation of the 0.929 m^2 (one square foot) diatomaceous earth filtration pilot plant.

Equipment	Specifications	Purpose
Raw water pump and motor	0-20 L/min (0-5 gpm) positive displacement rotary screw pump model #1 P898, Teel Corp.	Raw water feed
	Adjustable speed motor model #2Z8464, Dayton Corp.	Control pump
Bodyfeed pump and motor	0-0.3 L/min peristaltic variable speed master flex pump model #WZ1R057	Diatomaceous earth bodyfeed addition
Flowmeter	2-20 L/min O-ring seal flowmeter model #1305 B, Brooks Instr. Co.	Monitor flow rate through filter
Flowmeter	0-0.2 L/min model #A-369 Gilmont Corp.	Monitor flowrate of bodyfeed addition
Pressure gauges	0-207 kPa (0-30 psig), Weiss Corp.	Pressure readings
	0-690 kPa (0-100 psig), Weiss Corp.	Pressure readings
Manometer	147 cm Hg	Pressure readings
Mixers	0.025 kW (1/30 hp) single speed batch mixer	Mix plastic cooler
	0.186 kW (1/4 hp) single speed lightin mixer with timer	Mix milk cooler
	Two speed Waco Supreme power stirrer, Wilkens Anderson Co.	Mix bodyfeed addition
Turbidimeters	Hach ratio model #18900-10 HF Industries flowthrough model #DRT200	Measure turbidity
Accessory Pumps	March piston metering pump model #210-10, and 212	Concentrate *Giardia* influent sample
	Marine utility pump model #1P579C, Teel Corp.	Drain and fill tanks

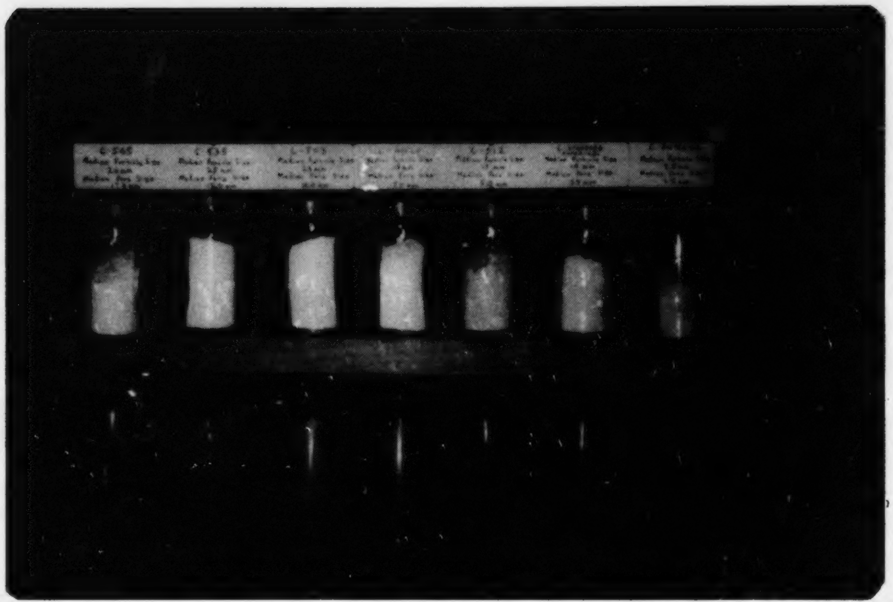


Figure 12. Photograph showing samples of seven grades of diatomaceous earth.

Reproduced from best available copy.

Figure 13. Photograph showing Standard Super-Cel, Filter Cel, and Hyflo Super-Cel grades of diatomaceous earth, as shipped in 50 pound bags.

Control of Operating Conditions

Table 5 lists the independent variables which were controlled during test runs. The manner in which these variables were controlled is described in this section.

Grade of diatomaceous earth

Seven grades of diatomaceous earth, as listed in Table 5, were used in the test program. Figure 12 is a photograph showing seven sample bottles containing these different grades. Each grade has a powder consistency. Figure 13 is a photograph showing three grades of diatomaceous earth as used from 50 pound bags.

Run time

Run time indicates the maximum duration of a test run. Giardia test runs were of two hours duration, while total coliform bacteria and standard plate count bacteria test runs lasted five hours or less. One Giardia cyst test was conducted for a duration of sixteen hours.

Headloss

Headloss was permitted to increase to 276 kPa (40 psi) if necessary during a given run. This variable was not controlled.

Hydraulic loading rate

The hydraulic loading rate was maintained constant throughout any given test run. This was done by using a variable speed positive displacement pump. The operating range was 2 to 20 L/min. Pressure and flow surges were reduced with a pressure dampener located between the pump and filter. A flow meter was used to monitor the flow during a test run.

Temperature

A temperature controlled milk cooler, shown in Figure 14, was used to maintain a constant temperature in the raw water feed tank. All laboratory tests in which Giardia cysts were used were performed at a constant temperature of 5°C or 15°C. Giardia cyst viability is uncertain at temperatures higher than 15°C. Other laboratory testing, in which Giardia cysts were not used, was done at ambient water temperatures, which ranged from 11°C to 19°C. Field testing was done under ambient temperature conditions.

Influent Giardia cyst concentration

To obtain the "design" Giardia cyst concentration in the raw water feed, a pre-counted cyst concentrate was added to a known volume in the raw water feed tank. To check the design cyst concentration in the feed tank, samples were withdrawn and then concentrated using the 5 micrometer pore size, 142 mm membrane filter sampling technique, described subsequently.

Figure 14. Temperature-controlled milk cooler.

During each test run, the raw water suspension containing Giardia cysts was mixed continuously to avoid settling of the cysts.

Influent coliform and standard plate count bacteria concentration

The influent total coliform concentration was varied by addition of primary settled sewage. The standard plate counts in the feed tank associated with this process ranged from 750 per ml to 3 million per ml.

Alum concentration

The diatomaceous earth was coated with alum by mixing a designated concentration of alum and diatomaceous earth in a concentrated solution. The precoat and bodyfeed were made up from this concentrate based on the weight of the diatomaceous earth. Allied chemical liquid alum was used. The concentration was measured in terms of grams alum (as $Al_2(SO_4)_3 \cdot 14H_2O$) per gram of diatomaceous earth, as described in Appendix H-1.

Precoat thickness

The diatomaceous earth precoat application rate was 0.1 kg/m^2 for all tests. This is within the recommended range of 0.05 to 0.1 kg/m^2. The 0.1

kg/m^2 rate was recommended by Logsdon, et al. (1981) and was determined to be the minimum required to prevent cyst breakthrough. Figure 15 illustrates the weighing process for addition of a measured amount of diatomaceous earth to the precoat slurry tank.

Bodyfeed Concentration

The bodyfeed concentration necessary for proper operation with Horsetooth Reservoir water was determined by several headloss versus time tests at different bodyfeed concentrations. The bodyfeed concentration giving a linear relationship was found to be 25 mg/L, which was used for all tests except the six which are noted. The bodyfeed turbidity ratio, cited in numerous publications, may be used as a guide, but actual testing is required for optimization. The 25 mg/L bodyfeed concentration was not an optimum when cysts were added to the Horsetooth water because of the additional particles and turbidity added, but it was adequate to perform the tests.

Figure 15. Photograph showing the weighing of diatomaceous earth for precoat addition.

Sampling and Measurement Techniques

Samples were obtained from the raw water feed tank and from the effluent of the filter for measurements of the dependent variables including turbidity, particle counts, total coliform bacteria, standard plate count bacteria, and Giardia cysts. In addition, elapsed time from beginning of run, headloss, hydraulic loading rate, and water temperature were measured. Instruments used are described in Table 6.

Sampling

Influent samples for measurements of turbidity, particle counts, total coliform bacteria, and standard plate count bacteria were grab samples obtained from the raw water feed tank. Grab samples were also taken on the effluent side of the diatomaceous earth filter using the sample tap shown in Figure 16. This tap is located on the effluent line before the overflow cup in the flow process as shown in Figure 11. When the sampling line is not used, it is fed into the overflow cup discharge, as shown in Figure 16. This assures a continuously flushed line.

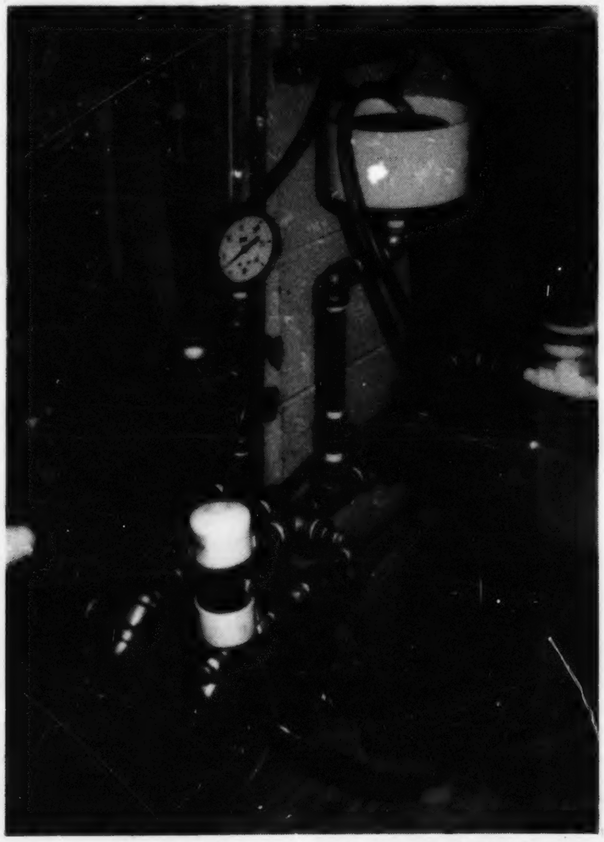


Figure 16. Effluent tap for taking turbidity, total coliform, standard plate count, and particle samples during diatomaceous earth filtration test runs.

Measurements of time, hydraulic loading rate, and temperature

Elapsed time was measured to the nearest minute. Hydraulic loading rate was measured by the flow meter listed in Table 6. This meter was standardized by volumetric measurements, as described by the quality control plan. The rating curve is given in Appendix J. Water temperature was measured by a mercury thermometer located on the influent tank. The residence time in the lines to the filter was only a few seconds. Velocities in all lines were well above that required to keep all particulate material suspended.

Headloss measurements

The differential pressure, or headloss, through the diatomaceous earth pilot plant is measured by comparing the difference in influent and effluent pressure as shown in Figure 17. The influent pressure can be measured by a manometer and by Pressure Gauge 1. The effluent pressure is measured by the elevation of the constant head overflow cup with respect to point B in the filter housing. This is shown in Figure 17 also. The equations seen in Table 7 indicate how the influent pressure (P_A) and effluent pressure (P_B) are calculated from the measurements.

Influent pressure measurements, P_A, at point A, were taken with the 147 cm mercury manometer shown in Figure 18. If the influent pressure exceeded that measurable by the manometer (greater than 120 centimeters of mercury), the filter mounted Pressure Gauge 1, shown in Figure 17, was used. The effluent pressure was constant for all laboratory experiments. This was maintained by using a constant head overflow cup.

The common parameter used to evaluate diatomaceous earth operations using various grades of diatomaceous earth is the time rate of pressure increase. This is determined by the change in influent pressure, P_A, with filtration time. These values are recorded as centimeters of mercury per hour. The influent pressure was observed at regular time increments for the duration of an experimental run. From these measurements a headloss versus run time relationship was obtained. Figure 19 is a typical headloss-run time relationship. The rate of change of headloss with respect to time, i.e. dh_L/dt, can be obtained from these measurements.

Table 7. Equations for determining influent and effluent pressures in diatomaceous earth filtration system.

Influent Pressure at A	Effluent Pressure at B
1. Pressure gauge on filter	1. Through overflow cup
P_A = gauge pressure at #1 + $h_1\gamma_\omega$	$P_B = h_5\gamma_\omega$
2. Manometer	
$P_A = h_4 \gamma_{Hg} - h_3\gamma_\omega$	

(Frictional losses are negligible)

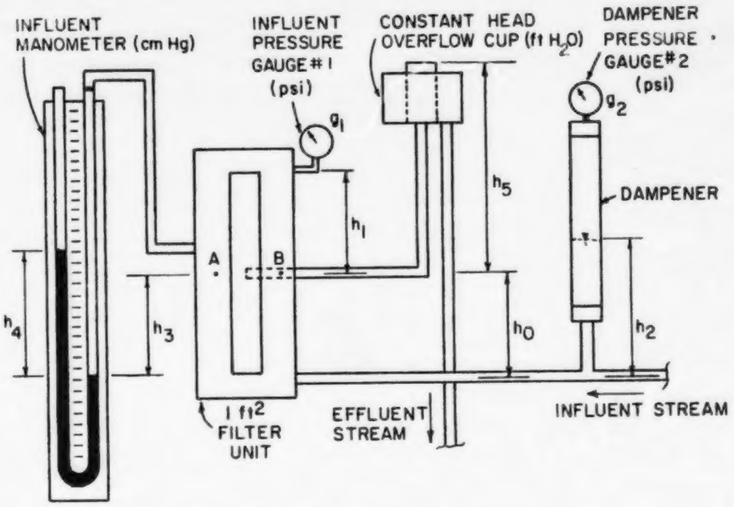

INFLUENT MANOMETER (cm Hg)
INFLUENT PRESSURE GAUGE # 1 (psi)
g_1
CONSTANT HEAD OVERFLOW CUP (ft H_2O)
DAMPENER PRESSURE GAUGE # 2 (psi)
g_2
DAMPENER
h_5
h_1
A
B
h_4
h_3
h_0
h_2
1 ft^2 FILTER UNIT
EFFLUENT STREAM
INFLUENT STREAM

Figure 17. Pressure measurements for diatomaceous earth filtration system.

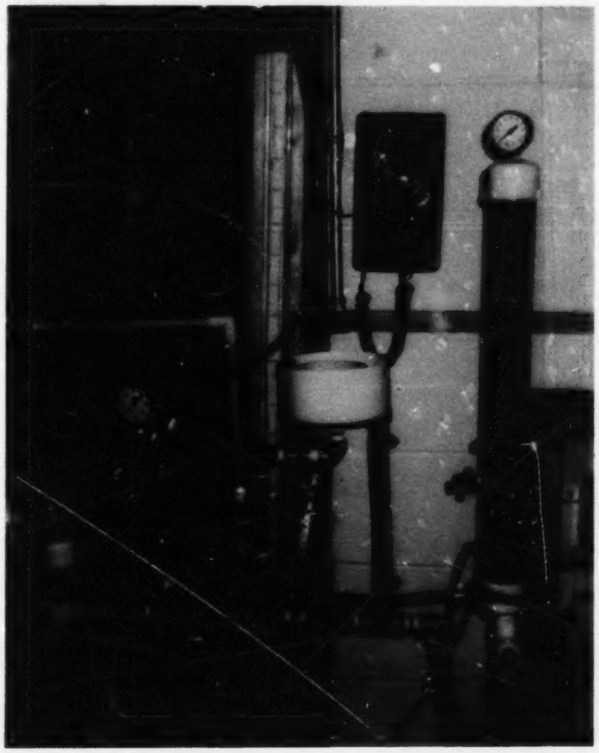


Figure 18. The mercury manometer, dampener, pressure gauges, and constant head overflow cup used in this experimentation to obtain pressure measurements.

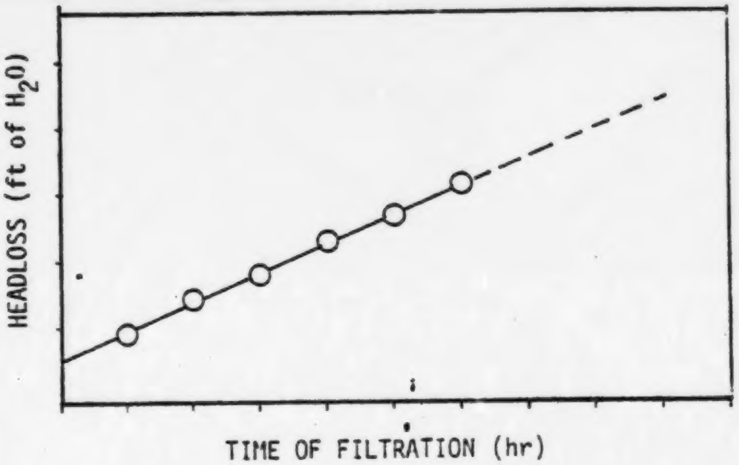


Figure 19. Typical plot showing experimentally determined headloss-run time relationship. Bodyfeed concentration is adjusted to provide linear relationship. Scales are highly variable, depending upon upon grade used.

Turbidity measurements

Turbidity was measured initially with an H. F. Instruments flow-through turbidimeter (model number DRT200). This turbidimeter is calibrated in terms of formazin turbidity units (FTU). This instrument was replaced after the first third of experimentation because it required continuous recalibration and was very sensitive to temperature and/or humidity changes, also it was not designed to measure turbidity below 0.08 NTU. A Hach Ratio turbidimeter (model number 18900) was used for the remaining tests. This instrument was selected for its stability and because it is being used by other researchers being sponsored by the EPA, i.e. turbidity results are thus comparable. The Hach Ratio turbidimeter shown in Figure 20 is calibrated in formazin turbidity units (FTU); the actual standardization is performed with latex standards provided by Hach which were calibrated against formazin standards.

Turbidity samples were taken from the effluent tap of the filter as shown previously in Figure 16 using one of the cuvettes supplied with the respective instrument used. After collecting the sample, the turbidity was measured immediately to avoid the possible settling of particles. Turbidity sampling was done concurrently with sampling for total coliform bacteria standard plate count bacteria, and particle counts.

Total coliform bacteria measurements

Total coliform bacteria were measured by the membrane filter technique according to the EPA "Microbiological Methods for Monitoring the Environment," December, 1978. Reporting is given as the number of colonies per 100 milliliters. M Endo MF agar was used as the enrichment medium for incubation of total coliform samples. Total coliform bacteria were used as the

Figure 20. Hach ratio turbidimeter model 18900 used for measuring turbidity samples.

performance indicator because it is most commonly used as an indicator of drinking water quality.

Total coliform samples were collected according to the protocols outlined in the paragraph, Pilot Plant Testing Protocol. Samples were collected in sterile 250 ml, autoclavable plastic Nalgene bottles. Immediately after collection the samples were refrigerated. Analyses were done within 30 minutes to four hours after the samples were obtained.

Standard plate count bacteria measurements

Standard plate count bacteria were measured by the standard plate count technique according to the EPA "Microbiological Methods for Monitoring the Environment." Reporting is given as the number of colonies per milliliter (No./ml). A tryptone glucose extract agar (Difco number DF 0002-01-7) was used as a nutrient medium instead of tryptone glucose yeast agar for standard plate count analyses. This is the medium specified by Standard Methods, 15th Ed. and this medium was in stock. Standard plate count analyses were performed from the same sample bottle used for total coliform analyses as explained in the previous section.

Particle count measurements

Particles were measured with a Coulter particle counter model number TA II shown in Figure 21. The units of particle measurement are the number of

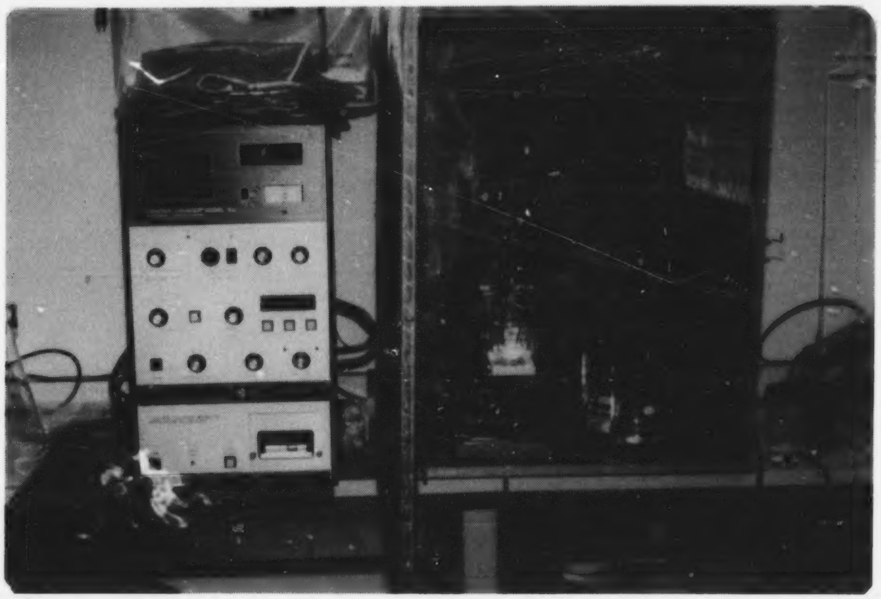


Figure 21. Coulter particle counter model number TA II used in diatomaceous earth testing.

particles per ten milliliters (No./10 ml). Grab samples were taken for particle analyses at the designated sampling intervals mentioned in the paragraph Pilot Plant Testing Protocol. These samples also were taken at the same time as the turbidity and bacteria samples. Sample bottles were prepared by thorough washing and then rinsing with particle free water.

Giardia cyst procurement and measurement

Procurement: The Giardia cysts used in this study were obtained from the feces of infected dogs. Special efforts were made to use fresh and viable cysts. Table 8 describes the sources of fecal samples which were processed to obtain cysts. Usually several million cysts can be obtained from a single fecal sample.

It should be noted that while we may refer to these cysts, obtained from dogs, as Giardia lamblia, this designation is not necessarily accepted by some microbiologists and parasitologists working in the field. The species Giardia lamblia is associated with man. Dr. C. P. Hibler takes the position in conversation that the cysts obtained from the dogs are indeed Giardia lamblia, since they are identical morphologically and there is cross-transmissability from dog to man, Davies and Hibler (1983). This position is confirmed further in the work reported by Hewlett, et al. (1982), who point out that giardiasis is cross-transmissable from man to dog.

Table 8. Sources used in obtaining dog fecal samples containing *Giardia lamblia* cysts.

Source	Conditions
1. Collaborative Radiological Health Laboratory (CRHL)	Approximately 200 dogs About 10 to 30 dogs are infected at any one time.
2. Humane Society for Larimer County	25-50 dogs, strays, runaways
3. Veterinary Teaching Hospital	Random samples brought into Parasite Diagnostic Laboratory
4. Oncology-Veterinary Teaching Hospital	12 dog pens, 10-30 dogs

The first step in procurement was to locate infected dogs. This was done by a reconnaissance visit to each of the locations indicated in Table 8. The reconnaissance was used to locate feces with characteristics of *Giardia lamblia* infection. The characteristics common to *Giardia lamblia* infected feces include soft, watery stools from puppies or stressed adult dogs. Fecal samples were collected in baggies, secured with twist-tie closures, and taken back to the laboratory for preparation and counting. Appendix C outlines the procedures used in processing the samples.

The *Giardia lamblia* cysts obtained in this procedure were stored under refrigeration until they were used in filtration experiments. Samples were examined every four days to determine their apparent condition and numbers while testing. No samples were stored longer than two weeks and, generally, for the diatomaceous earth filtration testing, no *Giardia lamblia* samples were stored longer than three days before use.

Sampling: *Giardia lamblia* cysts were concentrated from the water being sampled by passing the water through a 142 mm diameter polycarbonate membrane filter having a 5 micrometer pore size. Figure 22 is a photograph of one of the membrane filters. Figures 23 and 24 show a filter holder assembled and disassembled, respectively. This membrane filter sampling technique was developed at the University of Washington (Luchtel, 1982).

For effluent *Giardia* cyst sampling three to five membrane filters were set up with parallel plumbing, all operating simultaneously, as illustrated in the photograph shown in Figure 25. In this manner, 10 to 100 percent of the effluent stream was sampled. Figure 26 shows two line drawings of the membrane filter sampling system. Figure 26a shows the flow configuration used when the membrane filters, all operating in parallel, can accept the whole flow. When high flows were used a portion was diverted as shown in Figure 26b, to avoid rapid build-up of headloss across the membrane filter. In this case a pump was used to pressure the flow to the membrane filters and a tank was used to measure the sample volume. One to five filters were used in the configuration shown in Figure 26.

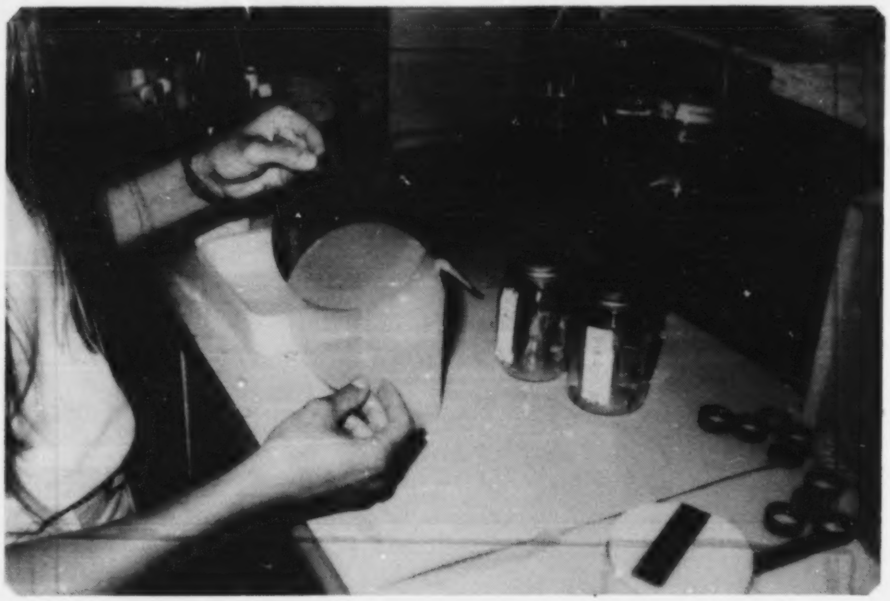


Figure 22. The 5 µm pore size 142 mm diameter polycarbonate filter used for sampling Giardia cysts.

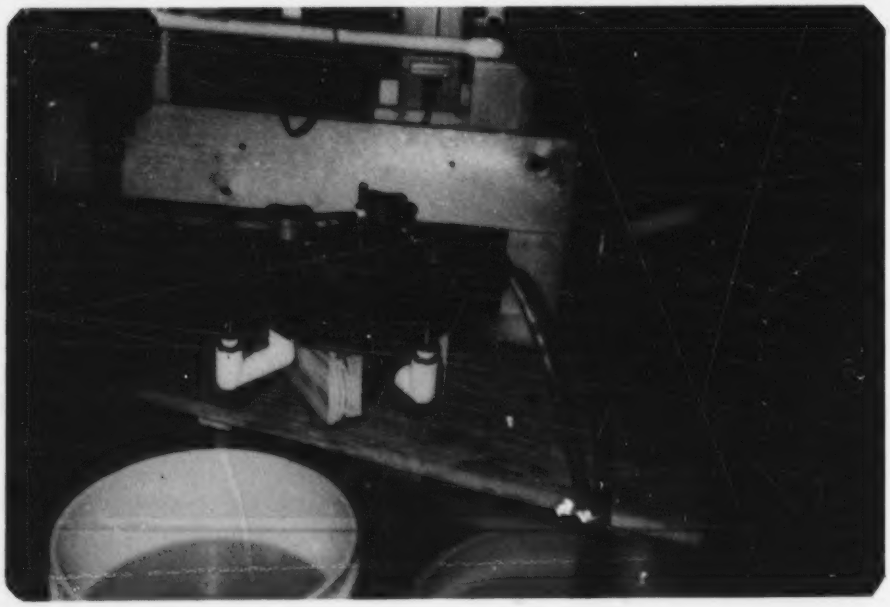


Figure 23. Assembled 142 mm diameter filter holder used in testing for Giardia cysts.

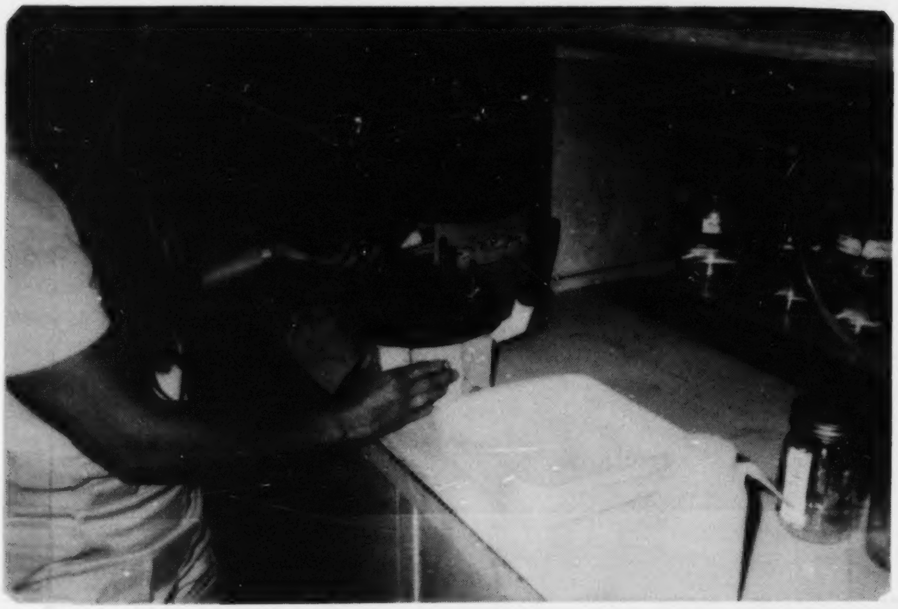


Figure 24. Diassembled 142 mm diameter filter holder used in testing for Giardia cysts.

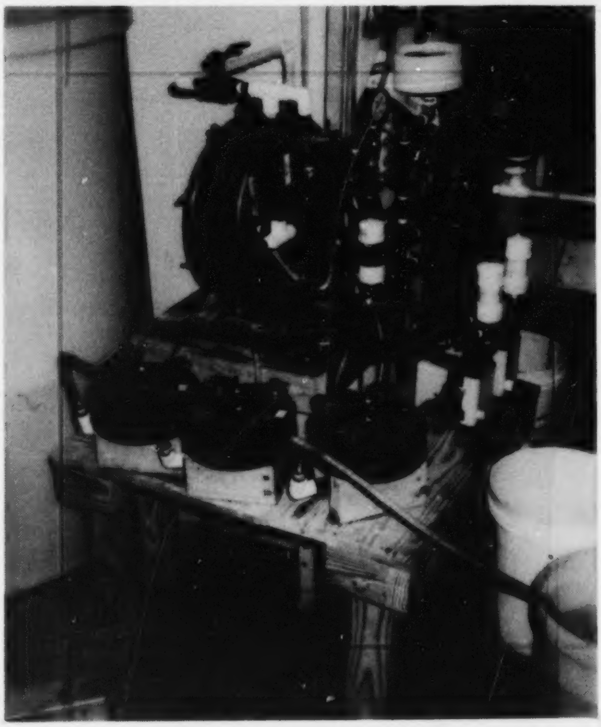
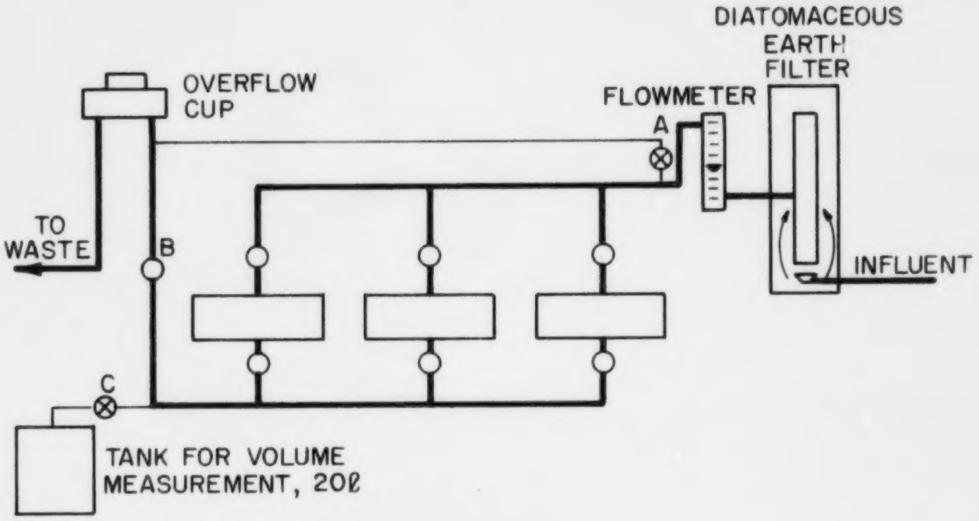
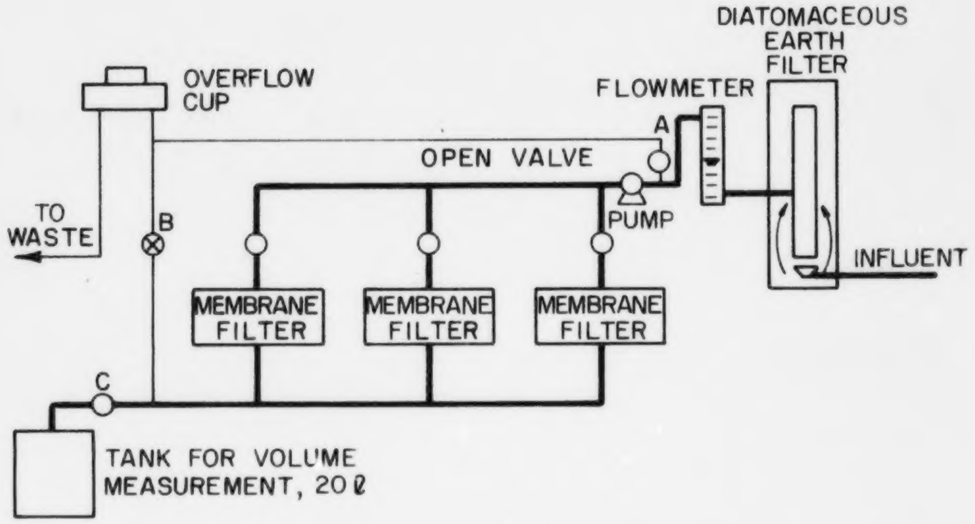


Figure 25. Three membrane filter holders operating in parallel, sampling for Giardia cysts.


DIATOMACEOUS EARTH FILTER
OVERFLOW CUP
FLOWMETER
A
TO WASTE
B
INFLUENT
C
TANK FOR VOLUME MEASUREMENT, 20ℓ

LOW FLOW CONFIGURATION


DIATOMACEOUS EARTH FILTER
OVERFLOW CUP
FLOWMETER
A
OPEN VALVE
PUMP
TO WASTE
B
INFLUENT
MEMBRANE FILTER
MEMBRANE FILTER
MEMBRANE FILTER
C
TANK FOR VOLUME MEASUREMENT, 20 ℓ

HIGH FLOW CONFIGURATION

Figure 26. Layout for membrane filter sampling of effluent from diatomaceous earth filtration pilot plant. One to five membrane filters were used in arrangement shown. When flow is too high for membrane filters valves C and A are open and valve B is closed; this permits volumetric flow measurement.

Table 9 shows the percentage of the effluent stream filtered through membrane filters for the hydraulic loading rates tested. The filter holders were disconnected when the pressure loss across the membrane filters exceeded 10 psi. When this occurred, the membrane filters were removed and washed, then new membranes were installed and the filters were placed back on line.

Table 9. Percentage of effluent stream sampled for Giardia cysts under various hydraulic loading rates.

Hydraulic Loading Rate (M/hr)	Percentage Ranges of Effluent Stream Sampled (%)
2.44	45-100
4.88	20-25
9.76	10-15

Counting: The Giardia cysts from the concentrated effluent samples were measured by the micropipette technique. The cyst counting protocol developed by Dr. C. P. Hibler and his associates in the Pathology Department at Colorado State University, is described in Appendix C. The results of the micropipette technique are reported by Dr. Hibler as the number of cysts found in the concentrated effluent sample. To obtain a cyst/liter concentration, this number is corrected for sampling recovery efficiency and then divided by the volume concentrated through the membrane filter. When zero cysts are recovered, the Giardia cyst reporting is in terms of detection limits. This is explained in Appendix D.

Pilot Plant Testing Protocol

The test protocol used during diatomaceous earth pilot plant filtration testing is described here. Test protocol A describes the filtration operations used for Giardia tests, while test protocol B describes the filtration operations used for bacteria tests only. Test protocol C describes the Giardia cyst sampling protocol for water in the feed tank, and test protocol D outlines the protocol for Giardia cyst sampling of the effluent stream.

Test protocols for other measurements are given in the Appendices. Appendix A contains the operating instructions for the diatomaceous earth pilot plant, provided by Manville Corporation. Appendix C describes the processing of dog fecal samples and the cyst counting techniques. Appendix G describes how to use the Coulter particle counter and Appendix H describes the test protocol for preparing alum coated diatomaceous earth.

(A) DIATOMACEOUS EARTH FILTRATION PILOT PLANT OPERATING PROTOCOL FOR GIARDIA LAMBLIA CYST TESTING

1. Fill filter feed tank with reservoir water and add cyst concentrate and sewage.

2. Fill filter housing with reservoir water.

3. Precoat the filter septum with 0.1 Kg (0.2 lbs) of diatomaceous earth.

4. Add 25 mg/L of chlorine to precoat tank and recycle one-half hour through effluent sample lines and filter precoat for disinfection.

5. Take grab samples from filter feed tank for total coliform, standard plate count, turbidity and particle analyses.

6. Concentrate *Giardia* sample from filter feed tank with membrane filter.

7. After one-half hour:
   a. Start bodyfeed to filter.
   b. Start raw water supply with measured quantity of *Giardia lamblia* cysts.
   c. Open filtrate effluent valve and close recycle valve.
   d. Discontinue precoat recycle.

8. Measure differential pressure.

9. Filter one-half hour to allow for wash out of chlorine residual.

10. Take samples from effluent tap for total coliform, standard plate count, turbidity and particle analyses.

11. Connect membrane filter units to effluent sample tap and pumps if flowrate is greater than 0.68 mm/s (1 gpm/ft^2).

12. Sample diatomaceous earth filtrate through membrane filters. Figure 26 shows three filters in parallel for *Giardia lamblia* cyst sampling.

13. Direct the remaining flow through the overflow cup.

14. Measure differential pressure.

15. Disconnect the membrane filters after the desired sampling time.

16. Measure differential pressure.

17. Take samples from effluent tap for total coliform, standard plate count, turbidity and particle analyses.

18. Take grab sample from influent tank for total coliform, standard plate count, turbidity and particle analyses.

19. Stop filtration and close valves.

20. Wash the membrane filters (see *Giardia* cyst sampling techniques).

21. Refrigerate *Giardia* and bacteria samples prior to counting analyses.

22. Wash membrane filter holders in hot, soapy water.

23. Wash diatomaceous earth cake from filter septum (see Appendix A, operating instructions for 1 ft^2 diatomaceous earth filter).

(B) PROCEDURES FOR BACTERIA REMOVAL TESTING BY DIATOMACEOUS EARTH FILTRATION

1. Follow steps 1-5 in *Giardia* cyst testing.

2. After one-half hour:
    a. Start bodyfeed to filter.
    b. Start raw water supply with measured quantity of primary effluent sewage.
    c. Open filtrate effluent valve and close recycle valve.
    d. Discontinue precoat recycle.

3. Filter one-half hour to allow for washout of chlorine residual.

4. Measure differential pressure and take samples from effluent tap for total coliform, standard plate count, turbidity and particle analyses every hour.

5. a. Continue test run until the volume in the raw water supply tank is depleted or until the pressure gauge on the filter reaches 30 psi. The volume in the raw water tank pumped at 0.68 mm/s will be exhausted in approximately 5.5 hours.
    b. Take grab sample from raw water supply at beginning of test run and then after four hours of run time.

6. Measure differential pressure and take samples from effluent tap for total coliform, standard plate count, turbidity and particle analyses.

7. Refrigerate bacteria samples prior to analyses.

8. Stop filtration.

9. Wash diatomaceous earth cake from septum to clean filter (see Appendix A, operating instruction for 0.929 m^2 (1 ft^2) diatomaceous earth filter).

(C) FEED TANK *GIARDIA* CYST SAMPLING PROTOCOL USING MEMBRANE FILTERS

1. Wash membrane filter holders and membrane support with hot, soapy water.

2. Rinse with cold tap water.

3. Place filter on membrane support in filter holder. Screw top securely into place.

4. Using a small positive displacement pump described in the equipment list in Table 6, pump the feed tank water which has been spiked with Giardia cysts through the filter set-up as shown in Figure 27.

5. Collect the filtrate effluent for a volume measurement.

6. Filter the influent sample until 10 psi is reached on the pump-mounted pressure gauge or ten liters are concentrated.

7. Clean the membrane filter according to Steps 9-16 of the effluent Giardia sampling procedure which follows.

(D) EFFLUENT GIARDIA CYST SAMPLING PROTOCOL USING MEMBRANE FILTERS

1. Wash membrane filter holders and membrane support with hot, soapy water as shown in Figure 28. Rinse with cold tap water.

2. Place filter on membrane support in filter holder as shown in Figure 29. Screw top securely into place.

3. Place three to five membrane filters in parallel with tygon tubing, as shown in Figure 30.

4. Connect pumps if flowrate is greater than 0.678 mm/s (1.0 gpm/ft^2) and membrane filters to effluent sample tap.

5. After one-half hour of filtering to waste for chlorine washout, sample diatomaceous earth filtrate through membrane filters.

6. Monitor pressure gauges on pumps to membrane filters. Do not exceed 10 psi. When 10 psi or the designated filtration time is reached, discontinue membrane filtration process.

7. Remove membrane filter holders from pilot plant sampling tap and place on laboratory bench.

8. Shut down pilot plant or filter to waste.

9. Connect aspirator to effluent piping of membrane filter holder to draw off excess water as shown on Figure 31.

10. With an air hose, blow off excess water and particles from top of filter holder.

11. Open filter holder carefully so that the filter remains on the bottom half of filter holder.

12. Spray top piece of filter holder with distilled deionized water into clean dish.

13. Carefully lift stainless steel membrane support from bottom half of filter holder.

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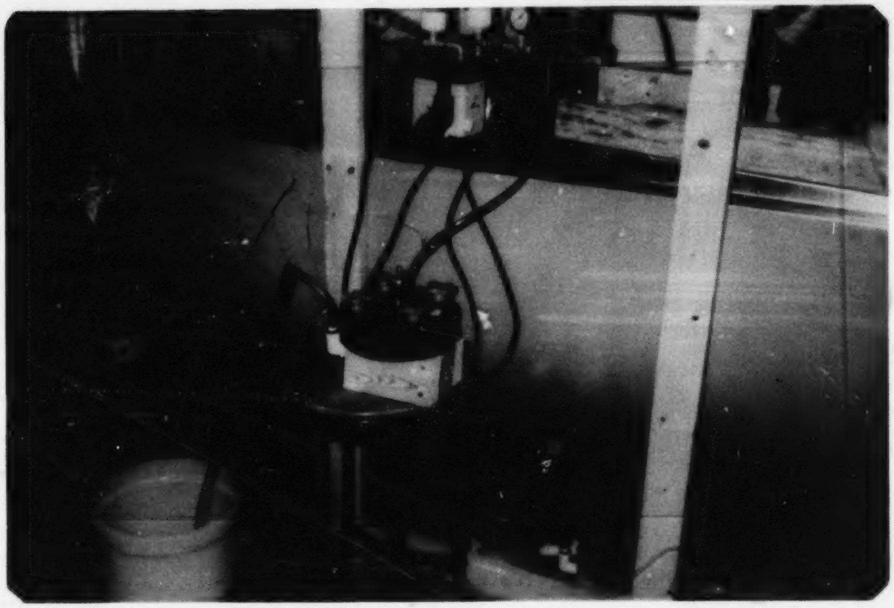


Figure 27. Membrane filter and pump set-up used to concentrate an influent Giardia cyst sample.

Figure 28. Washing the membrane filter holder to make the filter Giardia "free".

Figure 29. Placing membrane filter on stainless steel support in the filter holder.

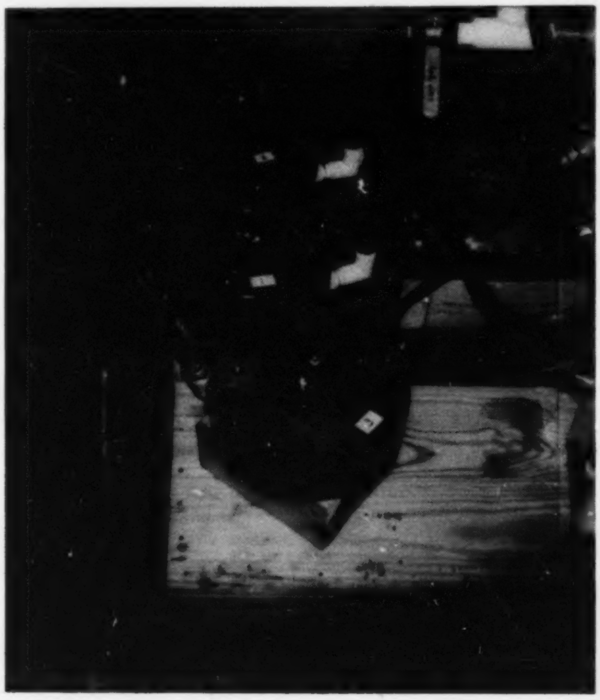


Figure 30. Three membrane filters connected in parallel by tygon tubing.

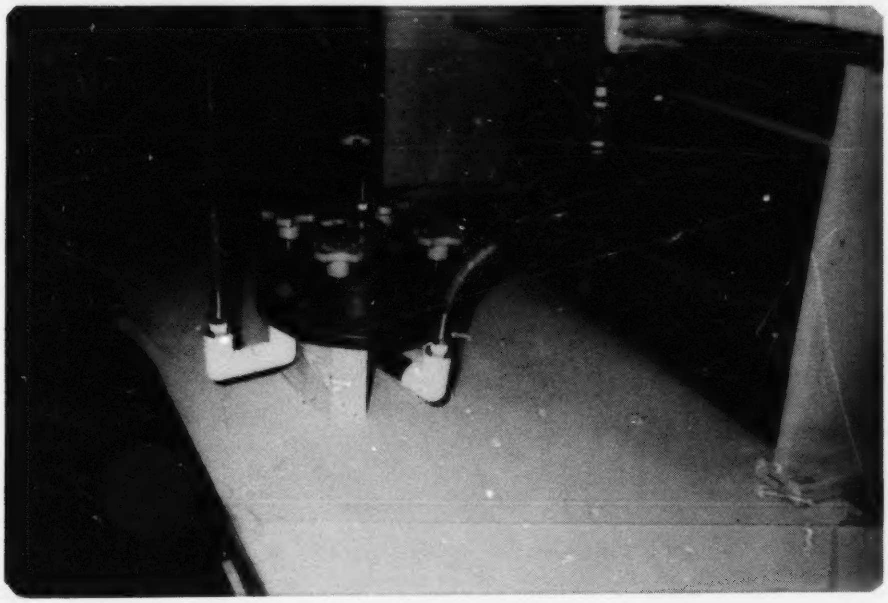


Figure 31. Aspirator connected to effluent piping of membrane filter holder to draw off excess water.

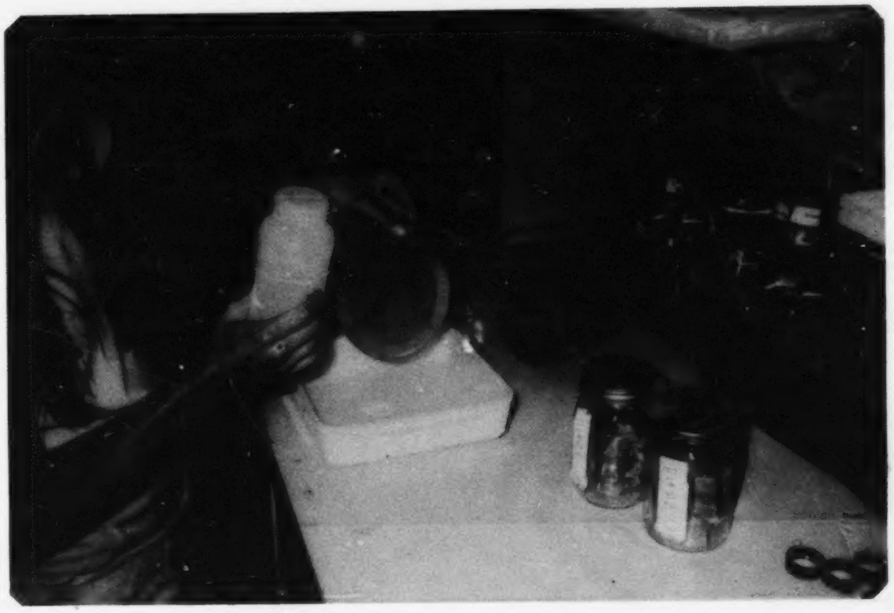


Figure 32. Spraying the membrane support and membrane filter with distilled water.

14. Spray membrane support and membrane filter with distilled water into dish as shown in Figure 32.

15. Remove the membrane filter for disposal; set membrane support aside for washing.

16. Spray the bottom piece of membrane filter holder with distilled deionized water into dish. Especially douse the influent piping of the filter holder.

17. Empty *Giardia* collection dish into clean sample jar. Spray the sides of the dish into the sample jar as shown in Figure 33. Refrigerate the sample prior to counting analysis.

18. Wash filter holder and membrane support to eliminate contamination, as was shown in Figure 28.

Data Processing

Measurements of operating conditions were taken during each test run and were recorded on the data coding sheet shown in Figure 34. Measurements taken include time, turbidity, temperature, pressure, flowrate, and bodyfeed rate. These measurements were taken once each hour, or every 15 minutes during alum testing.

Figure 35 shows the data coding sheet used to record the data for the dependent variables. Measurements included particle counts, total coliform bacteria, standard plate count bacteria, and *Giardia* cysts. The data sheet also shows the run number, time and date the sample was obtained, sample number, location of sample, and results of measurements.

Quality Control

Quality control refers to a protocol in which measurements obtained by various instruments and methods are compared with a known standard or calibration. This procedure is used to assure valid analytical results. Quality control procedures are described in the "Quality Control Plan" (Bellamy, 1981) developed for the overall EPA project. This plan was augmented to account for possible plumbing leaks. A brief description of the quality control procedures is described below and Appendix J contains some of the forms use for quality control.

Flowmeters and pumps

The flowmeters and pumps were calibrated by time-volume measurements. The pump settings were calibrated at filter influent pressures of 0, 30, and 60 psi. The calibration curves for the raw water feed pump and bodyfeed slurry pump are included in Appendix J. The raw water feed pump was also used as the precoat slurry pump.

Incubator and water bath: The incubator temperature and the water bath temperature were both checked every other day when in use. Appendix J contains an example of an incubator equipment and operation record.

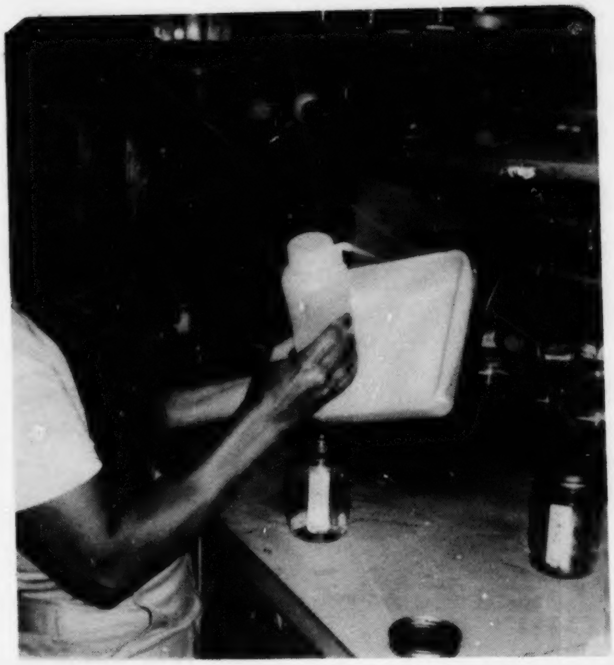


Figure 33. Emptying the Giardia cyst collection dish into sample jar, and spraying dish bottom and sides.

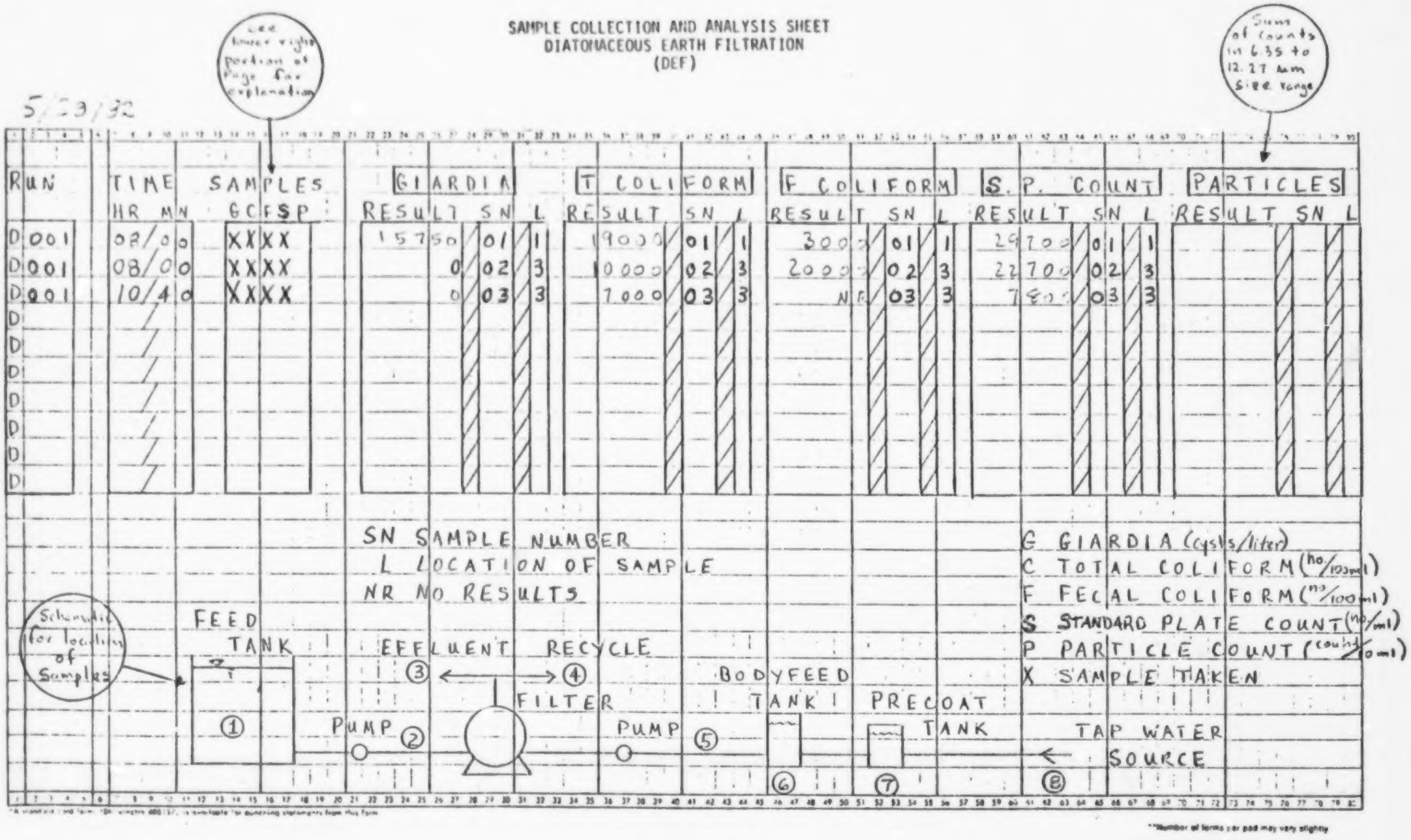
Bacterial analyses: The agars and analyses used in microbiological testing were checked according to the following procedures:

1. Total Coliform Analyses

   a. Filter sterility is monitored by randomly choosing one of the 0.45 µm filters and placing it on a petri dish of the total coliform agar. The procedure followed is the same as that for routine analysis except no water is filtered. The plate is checked for growth after 24-hour incubation. This is done daily during sample processing. Appendix J contains typical results of filter sterility monitoring.

   b. Whenever possible, duplicate plates of each sample dilution are prepared. The average number between the duplicate plates is reported.

   c. Total coliform plates are always refrigerated before use and are not kept longer than 10 days.



SAMPLE COLLECTION AND ANALYSIS SHEET
DIATOMACEOUS EARTH FILTRATION
(DEF)

5/23/82

see lower right portion of page for explanation

Sum of counts in 6.35 to 12.27 μm size range

RUN	TIME HR MN	SAMPLES GCFSP	GIARDIA RESULT	SN	L	T COLIFORM RESULT	SN	L	F COLIFORM RESULT	SN	L	S.P. COUNT RESULT	SN	L	PARTICLES RESULT	SN	L
D001	08/00	XXXX	15750	01	1	19000	01	1	3000	01	1	29700	01	1			
D001	08/00	XXXX	0	02	3	10000	02	3	2000	02	3	22700	02	3			
D001	10/40	XXXX	0	03	3	7000	03	3	NR	03	3	7800	03	3			
D	/																
D	/																
D	/																
D	/																
D	/																
D	/																
D	/																

SN SAMPLE NUMBER
L LOCATION OF SAMPLE
NR NO RESULTS

G GIARDIA (cysts/liter)
C TOTAL COLIFORM (no/100ml)
F FECAL COLIFORM (no/100ml)
S STANDARD PLATE COUNT (no/ml)
P PARTICLE COUNT (counts/10ml)
X SAMPLE TAKEN

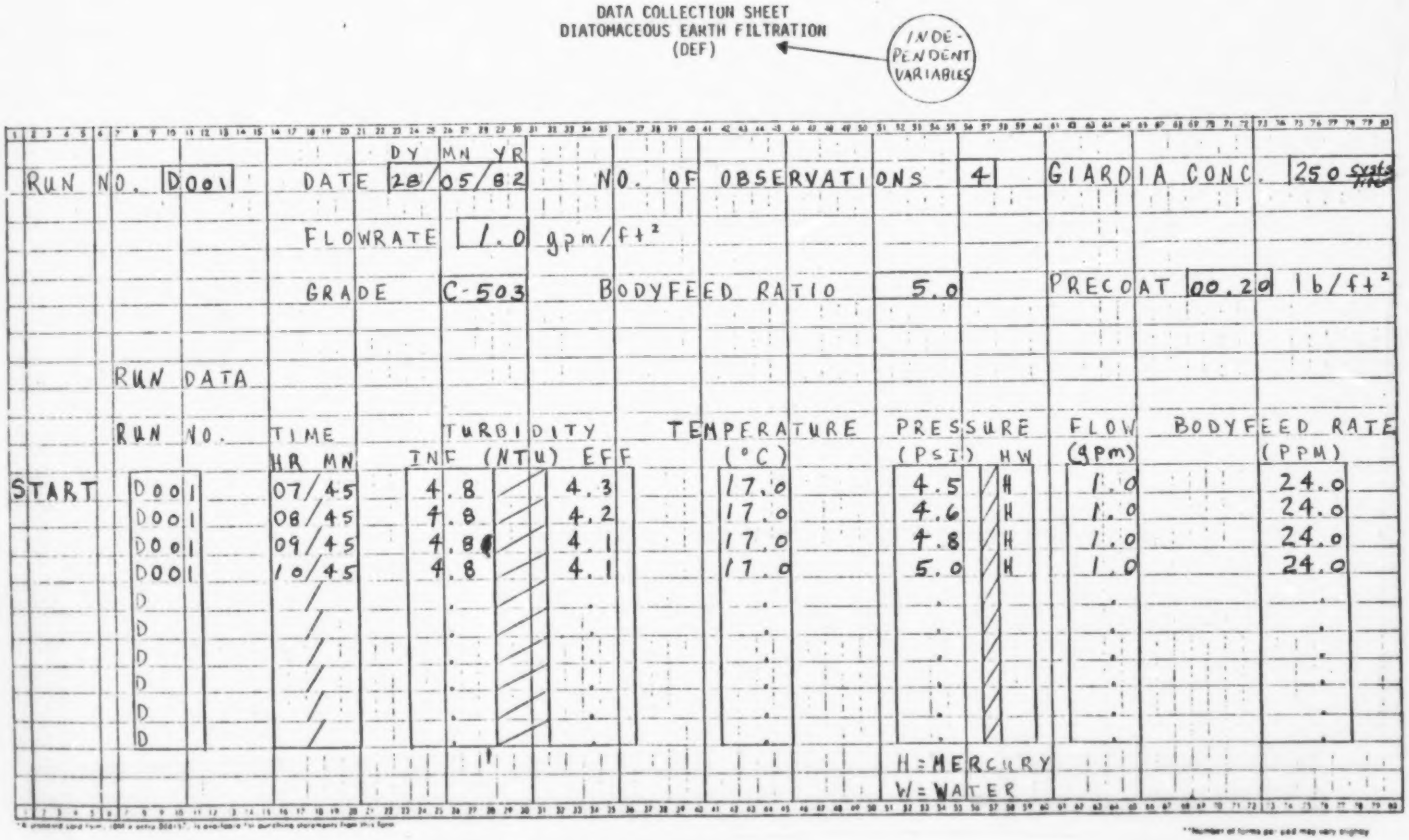
Schematic for location of samples

FEED TANK
①
PUMP ②
EFFLUENT ③
RECYCLE ④
FILTER
PUMP ⑤
BODYFEED TANK ⑥
PRECOAT TANK ⑦
TAP WATER SOURCE ⑧

*A standard card form, IBM electro 888157, is available for punching statements from this form

**Number of forms per pad may vary slightly

Figure 34. Computer format data collection form for dependent variables.



DATA COLLECTION SHEET
DIATOMACEOUS EARTH FILTRATION
(DEF)

INDEPENDENT VARIABLES

RUN NO. D001 DATE DY MN YR 28/05/82 NO. OF OBSERVATIONS 4 GIARDIA CONC. 250 cysts/liter

FLOWRATE 1.0 gpm/ft²

GRADE C-503 BODYFEED RATIO 5.0 PRECOAT 00.20 lb/ft²

RUN DATA

	RUN NO.	TIME HR MN	TURBIDITY (NTU) INF	TURBIDITY (NTU) EFF	TEMPERATURE (°C)	PRESSURE (PSI)	HW	FLOW (gpm)	BODYFEED RATE (PPM)
START	D001	07/45	4.8	4.3	17.0	4.5	H	1.0	24.0
	D001	08/45	4.8	4.2	17.0	4.6	H	1.0	24.0
	D001	09/45	4.8	4.1	17.0	4.8	H	1.0	24.0
	D001	10/45	4.8	4.1	17.0	5.0	H	1.0	24.0
	D	/	.	.	.	.		.	.
	D	/	.	.	.	.		.	.
	D	/	.	.	.	.		.	.
	D	/	.	.	.	.		.	.
	D	/	.	.	.	.		.	.
	D	/	.	.	.	.		.	.

H = MERCURY
W = WATER

Figure 35. Computer format sample collection and analysis form for independent variables.

2. Standard Plate Count Bacteria

a. Standard petri dishes are poured with no water sample to check sterility of the media. This is done at least every other day during testing. Appendix J contains typical results of media sterility monitoring.

b. Duplicate plates of each sample dilution are prepared and counted. The average number between the duplicate plates is reported.

c. Plate count agar is always refrigerated before use and is not kept longer than two weeks.

Giardia cysts: To ensure condition and number, the concentrated cyst sample used to spike raw water with Giardia cysts for pilot plant testing is recounted every four days. All samples are stored under refrigeration, with two weeks maximum storage time.

Giardia sampling: The quality control procedures for Giardia cyst handling and analysis are described in Appendix D. In addition, measurements were made to determine if there were any cyst loss due to pumping with the main filter feed pump or with the sampling pumps; none were found.

Membrane filter holders

The membrane filter holders must be free of Giardia cysts prior to use. This is accomplished by washing the filter holders in hot soapy water and rinsing with cold tap water.

Diatomaceous earth filter unit

Plumbing leaks: The diatomaceous earth filter was checked every five test runs to determine if a leak had developed in the septum or manifold. Raw water spiked with primary effluent sewage was filtered through 0.1 kg/m^2 of Filter-Cel medium. The effluent was sampled for coliforms; if any were detected in the effluent sample, a leak was presumed present. If a leak was detected the system was examined for any obvious problems. If none were seen the O-ring seal between the septum and the housing was refitted and the detection procedure was repeated.

Chlorine: Prior to bacteria removal test runs, the diatomaceous earth filter plumbing system was disinfected. The filter unit and sampling lines were disinfected by recycling water with a chlorine residual greater than 5 mg/l through the system for thirty minutes.

Particle counting

The analytical procedures and quality control measures for particle counting are outlined in Appendix G.

SECTION 5

PILOT PLANT RESULTS - LABORATORY WORK

Table 10 summarizes the processed data from forty-eight diatomaceous earth filtration test runs conducted at the Engineering Research Center using water from Horsetooth Reservoir. It shows the average influent and effluent concentrations and average removal percentages for:

a. total coliform bacteria
b. standard plate count bacteria
c. turbidity
d. particles
e. Giardia cysts

Table 10 also shows the test conditions, e.g., grade of diatomaceous earth, filtration rate, temperature, duration of run, and rate of pressure increase. Appendix E contains the raw data for the same forty-eight diatomaceous earth filtration test runs from which Table 10 was derived. The results are reviewed in this section.

Removal Percentages

The average influent and effluent concentrations and the average removal percentages of total coliform bacteria, standard plate count bacteria, turbidity, particle counts, and Giardia cysts for forty-eight test runs are shown in Table 10. The average influent and effluent values were calculated from all data for a given parameter during a test run. The average percent removal was calculated using the average influent and effluent values.

Total coliform bacteria

Table 10 shows that the total coliform bacteria removal percentages range from 27 percent to greater than 99.97 percent for twenty-eight tests performed on the seven grades of diatomaceous earth without chemical addition. Table 10 also shows that for six alum-coated diatomaceous earth filtration test runs, the total coliform removal percentages ranges from 98 percent to 99.86 percent using diatomaceous earth grades C-545 and C-503 at alum-diatomaceous earth ratios ranging from 0.04 to 0.08 grams/gram.

Standard plate count bacteria

Table 10 shows that the standard plate count bacteria removal percentages range from 50 percent to 99.99 percent for thirty-two tests performed on the seven grades of diatomaceous earth without chemical

Table 10. Average removals of total coliform bacteria, standard plate count bacteria, Giardia cysts, turbidity, and particle counts by diatomaceous earth filtration for forty-eight test runs. Compiled from data in Table E-1.

IDENTIFICATION			TEST CONDITIONS				TOTAL COLIFORM			STANDARD PLATE COUNT		
Date	Run Number	Diatomaceous Earth Grade	Temp. (°C)	Hydraulic Loading Rate (m/hr)	Dura. of Test Run (min)	Rate of Pressure Increase (cm Hg/hr)	Influent (no./mL)[10]	Effluent (no./mL)[10]	Percent Removal (%)	Influent (no./mL)[10]	Effluent (no./mL)[10]	Percent Removal (%)
7/4/82	13	C-545	5	2.44	90	0.0	1765	297	77	55	13.0	83
7/26/82	18	C-545	13	2.44	90	0.1	9800	246		ND	ND	75
7/27/82	20	C-545	5	2.44	90	0.0	44500	16300	45	30000	16500	63
7/30/82	28	C-545	5	2.44	370	0.1	79000	48800	28	34000	24600	38
8/26/82	41	C-545	12	2.44	55	ND	ND	ND		ND	ND	
9/30/82	42	C-545	13	2.44	160	1.5	ND	ND		ND	ND	
10/5/82	43	C-545	15	2.44	340	0.5	ND	ND		ND	ND	
10/12/82	45	C-545	14	2.44	310	2.5	ND	ND		ND	ND	
7/14/82	14	C-545	5	4.88	90	0.4	1765	467	64	55	20.0	73
7/26/82	19	C-545	13	4.88	90	1.0	9800	6890		ND	ND	30
7/27/82	21	C-545	5	4.88	90	0.2	44500	16400	35	30000	19500	63
7/26/82	17	C-545	5	9.76	90	2.0	8300	3560		ND	ND	57
7/28/82	26	C-545	5	9.76	90	0.6	7700	3740	27	4800	3500	51
10/14/82	46	C-545	16	2.44	360	0.1	15633	7870	70	12167	3533	50
11/18/82	49	C-545	14.0/10.5[3]	2.44	980	0.8	ND	ND		ND	ND	
7/16/82	15	C-535	5	2.44	90	0.0	2025	550	>79	36	<7	73
7/16/82	16	C-535	5	4.88	90	0.2	2025	240	92	36	3	88
7/13/82	11	C-503	5	2.44	90	0.0	2430	59	<96	27	<1	97
7/27/82	23	C-503	13	2.44	90	0.0	7300	2700	69	6100	1900	63
7/28/82	25	C-503	15	2.44	90	0.0	75300	22900	73	36000	9800	70
10/7/82	44	C-503	15	2.44	285	0.0	ND	ND		ND	ND	
8/6/82	32	C-503	13	2.44	330	0.0	6600	2936	68	4450	1418	55
10/21/82	47	C-503	14.5	2.44	330	0.1	11600	5777	80	13500	2614	50
7/13/82	12	C-503	5	4.88	90	0.2	2430	144	>96	27.5	<1.0	94
7/27/82	22	C-503	13	4.88	90	0.2	8250	2755	48	5450	2850	67
7/28/82	24	C-503	5	4.88	90	0.5	75300	26950	48	36000	18700	64
7/28/82	27	C-503	13	9.76	90	1.4	10200	3965	46	6000	3250	61
7/12/82	9	Hyflo	5	2.44	90	0.1	1945	120	>97	39.0	<1.0	94
8/3/82	29	Hyflo	12	2.44	330	0.0	7350	4216		ND	ND	42
8/5/82	31	Hyflo	13	2.44	330	0.0	9050	3125	83	4000	685	65
7/12/82	10	Hyflo	5	4.88	90	0.1	2000	17	>97	38	<1.0	99
8/9/82	33	C-512	15	2.44	330	0.5	4250	946	>99	1050	<11.7	78
8/11/82	35	C-512	14	2.44	330	0.5	3600	736	97	2380	71	79
8/4/82	30	STANDARD[7]	13	2.44	330	1.8	9250	336	>99	6100	<2	96
8/18/82	38	STANDARD	11	2.44	403	2.2	2955000	72	99	32500	54	99
8/19/82	39	STANDARD	12	2.44	630	3.8	8200	164	ND	<10000	24	98
8/10/82	34	FILTER[8]	14.5	2.44	115	59.5	3950	<2	99	85	<1.0	99
8/11/82	36	FILTER	13.0	2.44	120	53.4	990	3	99	640	<1.0	99
11/5/82	48	C-545 4% Alum	19.0	2.44	150	7.4	26125	1300	99	3450	34	95
11/20/82	50	C-503[9] 5% Alum	14.5	2.44	300	6.0	750	155	98	4975	98	79
12/2/82	51	C-545 5% Alum	13.5	2.44	300	17.0	4120	59	99	5800	8	99
12/8/82	52	C-503 5% Alum	13.5	2.44	210	12.7	2277	154	99	6950	30	93
12/8/82	53	C-503 5% Alum	13.5	2.44	300	19.1	18750	81	98	6150	96	99
12/18/82	54	C-545 8% Alum	12.5	2.44	240	35.5	27200	131	99	7100	12	99
12/19/82	55	C-545 5% Alum 0% B.F.	12.5	2.44	240	2.6	ND	ND		ND	ND	
12/19/82	56	C-545 5% Alum 0% Precoat	13.5	2.44	120	5.0	ND	ND		ND	ND	
12/20/82	57	C-545 2% Alum	12.5	2.44	180	2.9	ND	ND		ND	ND	
1/10/83	58	C-545 5% Alum 0% Precoat	12.0	2.44	300	9.8	ND	ND		ND	ND	

Table 10. continued.

	MEASUREMENTS								
	GIARDIA CYSTS			TURBIDITY			PARTICLE COUNTS from 6.35 to 12.70 µm		
Run Number	Influent (cysts/liter)[10]	Effluent[1] (cysts/liter)[10]	Percent Removal[2] (%)	Influent (NTU)	Effluent (NTU)	Percent Removal (%)	Influent (count/10mL)	Effluent (count/10mL)	Percent Removal (%)
13	100	<0.701	>99.299	3.5	3.3	6	831	37	95
18	100	<0.461	>99.539	4.2	3.6	14	776	81	90
20	500	<0.465	>99.907	4.4	3.5	20	2447	78	97
28	770	<0.326	>99.958	4.6	3.8	17	3280	136	96
41	38600	25.148	99.925	ND	ND		ND	ND	
42	10000	<0.112	>99.998	9.1	7.0	24	ND	ND	
43	5460	<0.108	>99.998	ND	ND		ND	ND	
45	8850	<0.063	>99.999	6.6	ND		ND	ND	
14	100	<0.425	>99.575	3.5	3.4	4	669	29	96
19	100	<0.323	>99.677	4.2	3.6	4	776	41	95
21	500	<0.326	>99.935	4.4	3.6	18	2447	145	94
17	100	<0.443	>99.557	4.2	3.7	12	1003	66	93
26	500	<3.342	>99.332	4.2	3.8	10	696	42	94
46	0			7.7	6.8	11	ND	ND	
49	2467[4]	<0.0004	>99.999	9.7[5]	8.4	14	ND	ND	
15	100	<0.423	>99.577	3.6	3.2	11	771	35	95
16	100	<0.453	>99.547	3.6	3.1	14	662	100	85
11	100	<0.257	>99.743	3.5	3.3	6	989	1284	ND[6]
23	0			4.2	3.6	15	865	162	81
25	500	<0.691	>99.862	4.4	3.7	15	2512	17	99
44	5460	<0.058	>99.998	ND	ND		ND	ND	
32	0			4.6	4.1	11	ND	ND	
47	0			7.6	7.0	8	ND	ND	
12	100	<0.481	>99.519	3.6	3.3	8	ND	ND	
22	100	<0.357	>99.643	4.2	3.6	14	865	47	95
24	500	<0.895	>99.821	4.3	3.5	18	2188	111	95
27	100	<0.532	>99.468	4.2	3.7	13	778	72	91
9	100	<0.478	>99.522	3.7	3.0	20	732	162	78
29	0			4.6	3.6	20	ND	ND	
31	0			4.6	3.8	18	ND	ND	
10	100	<0.694	>99.306	3.5	3.1	12	744	22	97
33	0			4.9	3.2	34	ND	ND	
35	0			4.6	3.3	28	ND	ND	
30	0			4.5	2.3	50	ND	ND	
38	0			5.0	2.5	49	ND	ND	
39	0			5.2	2.5	50	ND	ND	
34	0			4.6	0.1	97	ND	ND	
36	0			5.4	0.2	97	ND	ND	
48	0			8.0	1.1	86	ND	ND	
50	0			9.5	2.0	79	ND	ND	
51	0			9.4	0.1	98	ND	ND	
52	0			9.5	0.5	94	ND	ND	
53	0			9.8	0.1	99	ND	ND	
54	0			11.0	0.1	98	ND	ND	
55	0			10.0	3.4	66	ND	ND	
56	0			9.7	4.4	55	ND	ND	
57	0			9.5	3.2	66	ND	ND	
58	0			9.2	3.1	67	ND	ND	

Table 10. continued.

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[1] This value is the corrected effluent cyst concentration using the membrane filter sampling efficiency as found in Table 13.

[2] This value is determined by: 100 (Influent cyst concentration added to feed water - corrected effluent cyst concentration)/(Influent cyst concentration added to feed water)

[3] 14.0°C plastic tank containing Horsetooth Reservoir influent, 10.5°C milk cooler containing *Giardia* cysts.

[4] Average of 2467 cysts/liter added; $2.96\text{x}10^6$ cysts added intermittently for 80 minutes at 0, 4, 8, and 12 hours after start of run.

[5] Average of 9.9 NTU from milk cooler and 9.6 NTU from plastic tank.

[6] Percent removal cannot be calculated for this data.

[7] Grade - Standard Super Cel

[8] Grade - Filter Cel

[9] Bodyfeed concentration was increased from 25 mg/L to 50 mg/L after 180 minutes.

addition. Table 10 also shows that for six alum-coated diatomaceous earth filtration test runs, the standard plate count removal percentages ranged from 79 percent to 99.57 percent using diatomaceous earth grades C-545 and C-503 at alum-diatomaceous earth ratios ranging from 0.04 to 0.08 grams/gram.

Turbidity

Table 10 shows that the turbidity removal percentages range from 4 to 98 percent for thirty-four tests performed on the seven grades of diatomaceous earth without chemical addition. Table 10 also shows that for ten alum-coated diatomaceous earth filtration test runs, the turbidity removal percentages ranged from 55 to 99 using grades C-545 and C-503 with alum-diatomaceous earth ratios ranging from 0.02 to 0.08 grams/gram.

The four largest grades of diatomaceous earth, i.e. 545, 535, 503 and Hyflo, the normal water treatment grades, removed less than 21 percent of the turbidity particles found in the raw water source, Horsetooth Reservoir, when alum is not used. This poor removal is not indicative of most applications of diatomaceous earth filtration. The reason is due to the small particle sizes comprising the turbidity.

A relationship between the turbidity and the particles comprising the turbidity was developed by filtering Horsetooth reservoir water through different sized membrane filters. Table 11 shows the results. It is apparent that a 1 NTU standard cannot be met until the water is passed through a filter having a pore size smaller than 0.45 μm. This is not a common result and demonstrates the small size of the particles which account for the turbidity above 1 NTU. The small turbidity particles found in Horsetooth Reservoir are referred to here as "glacial flour". X-ray diffraction identified the particles retained by a 0.22 μm filter as kaolinite and montmorillonite clays. The results, reported by Dr. E. R. Baumann of Iowa State University, are in Appendix F.

Table 11. Turbidity removals by membrane filters having different pore sized for water from Horsetooth Reservoir.

Pore Size of Membrane Filter (μm)	Average Influent Turbidity (NTU)	Average Effluent Turbidity (NTU)	Percent Removal (%)
8	5.6	5.5	2
5	5.6	5.5	2
1.2	5.6	3.6	36
0.45	5.6	1.5	73
0.22	5.6	0.49	91

Particle counts

Table 10 shows the average influent and effluent particle concentrations and percent removals for the 6.35 to 12.70 µm size range for twenty diatomaceous earth filtration tests. These particle removal percentages ranged from 78 to 99 percent.

Table 12 shows the removal percentages for the 6.35 to 12.70 µm size range. It also compares the particle data to *Giardia* cyst removals. The data show that particle removals range between 53 and 99 percent for the twenty tests. The particles within the 6.35 to 12.70 µm size range bracket the nominal size of *Giardia* cysts, which is 7 to 10 µm. The *Giardia* cyst removals are at the detection limit for all test runs, while particle removals are more variable, but nevertheless high. The passage of particles is due in part to filter cake attrition. Appendix G contains the raw particle data for the 2.52 to 40.30 µm size ranges for the twenty filtration tests in which particle counting was performed.

Giardia cysts

Table 13 excerpted from the raw data in Table E-1, summarizes the results of twenty-five test runs in which *Giardia* cyst concentrations were measured (test run 45 was listed twice as described in the footnotes). This table shows the test conditions, the number of cysts recovered, and all other data used in calculating the detection limits and removal percentages.

Cysts detected in effluent: *Giardia* cysts were found in the effluent sample of only one of the thirty tests shown in Table 13. The one test run producing *Giardia* cyst breakthrough had an influent cyst loading of 33,600 cysts/liter. A total of 1,700 cysts were found when 208 liters of the diatomaceous earth filtrate were concentrated by the membrane filter technique. Zero *Giardia* cysts were found in the concentrated effluent samples from the other twenty-nine test runs.

Detection limits: Table 13 gives the membrane filter sampling efficiencies and the cyst detection limits for each test. The cyst detection limit is defined as the minimum number of cysts required in a sample to assure detection. The term means that the measurement technique, i.e., sampling and counting, is capable of detecting at least the concentration stated as the "detection limit." In other words, if the cyst detection limit is 3 per liter, and there are 3 or fewer cysts in the sample, we may miss detecting any. The lower the detection limit the better is the sampling accuracy. The detection limit concept is described in Appendix D.

All cyst detection limits were low, ranging from 0.058 to 3.342 cysts/liter for the thirty tests using *Giardia* cysts.

Effects of Operating Conditions on Dependent Variables

The effects of the various operating conditions on the removal efficiencies of total coliform bacteria, standard plate count bacteria, turbidity, particle counts, and *Giardia* cysts were determined by testing one

Table 12. Particle count removals in 6.35 to 12.70 μm size range compared with *Giardia* cyst removals for 20 diatomaceous earth filtration runs with different test conditions (plot 2).

Test Identification		Test Conditions			Particle Counts 6.35 to 12.70 μm			Giardia Cysts		
Date	No.	Grade	Hydraulic Loading Rate (m/hr)	Time (min)	Influent (count/10 mL)	Effluent (count/10 mL)	Percent Removal (%)	Influent (cysts/liter)	Effluent (cysts/liter)	Percent Removal^2 of Cysts (%)
7/27/82	13	545	2.44	30	831	67	92	100		
				90		7	99		0	>99.299
7/26/82	18	545	2.44	30	776	24	97	100		
				90		139	82		0	>99.539
7/27/82	20	545	2.44	30	2447	79	97	500		
				90		77	97		0	>99.907
7/30/82	28	545	2.44	0	3280	205	94	770		
				90		261	92			
				180		72	98			
				270		64	98			
				340		81	98		0	>99.958
7/14/82	14	545	4.88	30	669	36	95	100		
				90		22	97		0	>99.515
7/26/82	19	545	4.88	30	776	40	95	100		
				90		40	95		0	>99.677
7/27/82	21	545	4.88	30	2447	228	91	500		
				90		63	97		0	>99.935
7/26/82	17	545	9.76	30	1003	70	93	100		
				90		63	94		0	>99.557
7/28/82	26	545	9.76	30	696	53	92	100		
				90		32	95		0	>99.332
7/16/82	15	535	2.44	30	771	44	94	100		
				90		26	97		0	>99.577

Table 12. continued (part 2 of 2).

Test Identification		Test Conditions			Particle Counts 6.35 to 12.70 μm			Giardia Cysts		
Date	No.	Grade	Hydraulic Loading Rate (m/hr)	Time (min)	Influent (count/10 mL)	Effluent (count/10 mL)	Percent Removal (%)	Influent (cysts/liter)	Effluent (cysts/liter)	Percent Removal of Cysts[2] (%)
7/16/82	16	535	4.88	30	662	98	85	100	0	>99.547
				90		102	85			
7/13/82	11	503	2.44	30	989	2101	--	100	0	>99.743
				90		467	53			
7/27/82	23	503	2.44	30	865	31	97	100	ND[3]	ND
				90		294	66			
7/28/82	25	503	2.44	30	2512	16	99	500	0	>99.862
				90		18	99			
7/13/82	12	503	4.88	30	871	49	94	100	0	>99.519
				90		45	95			
7/27/82	22	503	4.88	30	865	64	93	100	0	>99.643
				90		18	98			
7/28/82	24	503	4.88	30	2188	178	92	500	0	>99.821
				90		45	98			
7/28/82	27	503	9.76	30	778	21	97	100	0	>99.468
				90		124	84			
7/12/82	9	Hyflo[4]	2.44	30	732	278	62	100	0	>99.522
				90		47	94			
7/12/82	10	Hyflo	4.88	30	744	28	96	100	0	>99.306
				90		17	98			

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[1] Design cyst concentration.

[2] Based on "detection limit" of cyst analysis technique when zero cysts are measued.

[3] No data for this measurement.

[4] Hyflo Super-Cel

Table 13. *Giardia* cyst counts for diatomaceous earth filtration tests.

IDENTIFICATION		CONDITIONS						RESULTS					
						Influent *Giardia*[1] Cyst Concentration						Effluent *Giardia* Concentration Corrected	*Giardia* Cyst
Date	Run No.	Grade	Filt. Rate (m/hr)	Temp. (°C)	Duration of Test (min)	Added to Feed Water (cysts/L)	Detected in Feed Water (cysts/L)	Effluent Volume Sampled (L)	Number of Cysts Detected in Analysis of Effluent Sample (No.)	Membrane Filter Sampling Efficiency[2] (%)	Cyst Detection Limit[3] (cysts/L)	for Sampling Efficiency[4] (cysts/L)	Percent Removal[5] (%)
7/14/82	13	545	2.44	5	90	100	27.7	103	0	27.7	0.701	<0.701	>99.299
7/26/82	18	545	2.44	13	90	100	50.5	86	0	50.5	0.461	<0.461	>99.539
7/27/82	20	545	2.44	5	90	500	229.0	94	0	45.8	0.465	<0.465	>99.907
7/30/82	28	545	2.44	5	340	770	75.0	633	0	9.7	0.326	<0.326	>99.958
9/30/82	42	545	2.44	13	145	10,000[8]	--	549	0	32.5[6]	0.112	<0.112	>99.998
10/5/82	43	545	2.44	15	150	5,460[8]	--	568	0	32.5[6]	0.108	<0.108	>99.998
10/12/82	45	545	2.44	14	260	8,850[8]	--	984	0	32.5[6]	0.063	<0.063	>99.999
8/26/82	41	545	2.44	12	55	3.36x10^4	--	208	1,700	32.5[6]	0.296	25.148	99.925
11/18/82	49	545	2.44	10.5	980	2,467	--	1,741	0	32.5[6]	0.0004	<0.0004	>99.999
7/14/82	14	545	4.88	5	90	100	44.4	106	0	44.4	0.425	<0.425	>99.575
7/26/82	19	545	4.88	13	90	100	65.9	94	0	65.9	0.323	<0.323	>99.677
7/27/82	21	545	4.88	5	90	500	330.0	93	0	66.0	0.326	<0.326	>99.935
7/26/82	17	545	9.76	5	90	100	47.0	96	0	47.0	0.443	<0.443	>99.557
7/28/82	26	545	9.76	5	90	500	31.5	95	0	6.3	3.342	<3.342	>99.332
7/16/82	15	535	2.44	5	90	100	45.5	104	0	45.5	0.423	<0.423	>99.577
7/16/82	16	535	4.88	5	90	100	45.5	97	0	45.5	0.453	<0.453	>99.547
7/13/82	11	503	2.44	5	90	100	76.4	102	0	76.4	0.257	<0.257	>99.743
7/28/82	25	503	2.44	5	90	500	127.0	114	0	25.4	0.691	<0.691	>99.862
10/7/82	44	503	2.44	15	275	5,460	--	1,041	0	33.0[6]	0.058	<0.058	>99.998
7/13/82	12	503	4.88	5	90	100	40.0	104	0	40.0	0.481	<0.481	>99.519
7/27/82	22	503	4.88	13	90	100	59.0	95	0	59.0	0.357	<0.357	>99.643
7/28/82	24	503	4.88	5	90	500	127.0	88	0	25.4	0.895	<0.895	>99.821
7/28/82	27	503	9.76	13	90	100	33.0	114	0	33.0	0.532	<0.532	>99.468
7/12/82	9	Hyflo	2.44	5	90	100	41.4	101	0	41.4	0.478	<0.478	>99.522
7/12/82	10	Hyflo	4.88	5	90	100	27.2	106	0	27.2	0.694	<0.694	>99.306
10/12/82	45	545[7]	4.88	14	40	8,850[8]	--	151	0	32.5[6]	0.408	<0.408	>99.995
4/17/83	F1	C-545	2.44	10	145	3,950	--	378	0	32.5	0.162	<0.162	>99.996
5/5/83	F3	C-545	2.44	3.5	105	1,000	229	227	0	22.9	0.385	<0.385	>99.962
5/6/83	F4	C-545	9.76	3.5	75	500	312	170	0	54.4	0.216	<0.216	>99.931
5/6/83	F5	C-545	4.88	3.5	90	1,000	740	248	0	74.0	0.109	<0.109	>99.989
5/6/83	F6	C-545	2.44	3.5	65	7,400	2248	132	0	30.8	0.492	<0.492	>99.993

Table 13. continued.

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[1] The "added" influent concentration, is the number of cysts contained in the feed tank as determined by analyzing the cyst concentration in a concentrated suspension of feces and adding this concentrate to a known volume of water in the feed tank. The "detected" influent concentration is obtained by sampling and analysis of the influent water from the feed tank.

[2] Membrane filter sampling efficiency = 100(Influent cyst concentration detected in feed water)/(Influent cyst concentration added to feed water).

[3] Cyst detection limit = (20 cysts/number of micropipette aliquots)/[(Membrane filter sampling efficiency)(Effluent volume sampled)]. The "20 cysts" is a multiplication factor inherent in the micropipette analysis technique.

[4] Effluent Giardia cyst concentration corrected for sampling efficiency = (No. of cysts detected in effluent)/[(Membrane filter sampling efficiency)/(Effluent volume sampled)]. If zero cysts were detected this value is taken as the detection limit.

[5] Giardia cyst percent removal = 100(Influent cyst concentration added to feed water - Effluent Giardia cyst concentration corrected for sampling efficiency)/(Influent cyst concentration added to feed water).

[6] The influent cyst concentration was not determined after the cysts were added to the storage tank. The sampling efficiency for these tests is taken as the average of all similar tests.

[7] This test is a 40 minute test performed at the end of test run No. 45. Test 45 was conducted at 2.44 m/hr until the last 40 minutes when the rate was increased to 4.88 m/hr.

[8] Cysts were added for the first hour and the total effluent was sampled for the entire period.

NOTE: All *Giardia* cyst analyses were conducted by the micropipette technique.

operating parameter through a range of values while holding all other operating conditions constant. The operating conditions were:

- a. grade of diatomaceous earth
- b. hydraulic loading rate
- c. influent concentrations of dependent variables
- d. headloss and run time
- e. temperature
- f. alum-coated diatomaceous earth

The results from forty-nine test runs, given in Table E-1, were used to determine the effects of the operating conditions and are discussed in this section.

Grade of diatomaceous earth

Table 14 gives the properties of the seven grades of diatomaceous earth tested, including color, median particle size, median pore size, density, and D_{10} size. The seven grades of diatomaceous earth, listed in Table 14, were tested for removal of total coliform bacteria, standard plate count bacteria, turbidity, particles, and Giardia cysts.

Total coliform, standard plate count, and turbidity: Table 15 shows the average removal percentages of total coliform bacteria, standard plate count bacteria, and turbidity for the six grades of diatomaceous earth tested. The table was constructed from data in Table E-1 for test runs lasting five hours.

This table shows that as the diatomaceous earth median particle size decreases and subsequently the median pore size, the total coliform bacteria, standard plate count bacteria, and turbidity removals increase. This table also shows that for the largest to the smallest diatomaceous earth particle size, total coliform bacteria removal ranged from 28 to greater than 99.8 percent, standard plate count bacteria removal ranged from 38 to 99.8 percent, and turbidity removal ranged from 17 to 98 percent.

Table 16 shows the average removal percentages for the parameters tested by grade of diatomaceous earth. Table 16 was constructed from the raw data of thirty-nine tests taken from Table E-1. All test runs for each grade of diatomaceous earth were averaged to give an overall picture of the performance of each grade, despite the differences in test conditions. This table shows the same trend as Table 15. As particle size decreases, total coliform bacteria, standard plate count bacteria, and turbidity removals increase.

Turbidity: The average turbidity removal percentages for the three largest grades of diatomaceous earth tested were approximately the same value: 12, 12, and 13 percent for C-503, C-535, and C-545, respectively as shown in Table 16. This result indicates that the majority of the particles comprising the turbidity in Horsetooth Reservoir water are smaller than the average pore size of these three grades of diatomaceous earth. Table 17 and Figure 36 demonstrate this by comparing pore size of membrane filters and pore size of diatomaceous earth to turbidity removal. As shown in Table 17

Table 14. Properties of diatomaceous earth grades tested.[1]

Grade	Color	Median Particle Size (μm)	Median Pore Size (μm)	Density (kg/m^3)		D_{10}, i.e. Particle Size at which 10% by Weight is Finer than Stated Size (μm)
				Dry	Wet	
Filter Cel	Gray	7.5	1.5	112	256	12.8
Standard Super-Cel	Pink	14.0	3.5	128	288	11.0
C-512	Pink	15.0	5.0	128	304	10.4
Hyflo Super-Cel	White	18.0	7.0			5.2
C-503	White	23.0	10.0	144	288	4.3
C-535	White	25.0	13.0	192	304	3.1
C-545	White	26.0	17.0	192	304	1.5

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[1] Constructed from Tables 1 and 2 in Manville Corp. Publication "Johns-Manville Celite filter aids for maximum clarity at lowest cost."

Table 15. Diatomaceous earth filter removals of turbidity, total coliform bacteria, and standard plate count bacteria for fivehour test runs.[1/] Removal data are averages of six effluent samples and two influent samples, respectively, taken during six test runs each lasting five hours. These data were compiled from Table E-1. Hydraulic loading rate was 2.44 m/hr for all tests of five hour duration.

Grade of D.E.	545	503	Hyflo Super-Cel	512	Standard Super-Cel	Filter Cel[2/]
Median Particle Size of D.E. (μm)	26	23	18	15	14	7.5
D.E. Particle Size 10% Finer than D_{10} (μm)	12.8	10.4	5.2	4.3	3.1	1.5
Median Pore Size (μm)	17.0	10.0	7.0	5.0	3.5	1.5
Turbidity Removal (%)	17.4	11.2	18.5	28.3	50.6	98.8
Influent NTU	4.6	4.6	4.6	4.6	4.5	5.4
Effluent NTU	3.8	4.1	3.8	3.3	2.3	0.1
Total Coliform Bacteria Removal (%)	28	68	83	97	>99.9	>99.8
Influent Conc. #/100 ml	34,000	4,450	4,000	2,380	6,100	640
Effluent Conc. #/100 ml	24,600	1,418	685	71	<1.7	<1
Standard Plate Count Bacteria Removal (%)	38	56	65	79	96	99.8
Influent Conc. #/ml	79,000	6,600	9,050	3,600	9,250	990
Effluent Conc. #/ml	48,800	2,936	3,126	737	337	2.5
Average Rate of Pressure Increase (cm Hg/hr)	0.02	0.02	0.10	0.48	1.84	40

[1/] Particle counting was not done on the five-hour test runs.

[2/] This test was discontinued when headloss became 30 psi which occurred at 120 min of run time.

Table 16. Removal percentages of total coliform bacteria, standard plate count bacteria, turbidity, particles, and *Giardia* cysts and average rate of pressure increase for seven grades of *diatomaceous* earth averaged for 38 tests. Calculated from data in Table E-1.

Grade of Diatomaceous Earth	545	535	503	Hyflo Super-Cel	512	Standard Super-Cel	Filter Cel
Number of tests	15	2	10	4	2	3	2
Median Particle Size (µm)	26.0	25.0	23.0	18.0	15.0	14.0	7.5
Total Coliform Removal (%)	49	85	69	93	98	99.9	99.9
Standard Plate Count Removal (%)	58	80	69	75	79	99	99.8
Turbidity Removal (%)	13	12	12	23	31	50	97.6
Particle Count Removal (%)	94.4	90.2	92.14	87.4	ND[1]	ND	ND
Giardia Cyst Removal (%)	>99.7	>99.5	>99.7	>99.4	ND	ND	ND

[1] No data (ND) taken.

Table 17. Comparison of average turbidity removals for 38 diatomaceous earth filtration test runs with turbidity removals by membrane filters. Diatomaceous earth data compiled from Table E-1 and membrane filter data is same as Table 11.

DIATOMACEOUS EARTH EXPERIMENTATION							MEMBRANE FILTER EXPERIMENTATION[3]			
Grade of Diatomaceous Earth	D.E. Particle Size 10% Finer than Weight[1] D_{10} (µm)	Diatomaceous Earth Median Particle Size[1] (µm)	D.E. Median Pore Size[1] (µm)	Average Influent Turbidity[2] (NTU)	Average Effluent Turbidity[2] (NTU)	Percent Removal (%)	Pore Size (µm)	Average Influent Turbidity (NTU)	Average Effluent Turbidity (NTU)	Percent Removal (%)
C-545	12.8	26	17	5.4	4.6	16	8	5.6	5.5	1.8
C-535	11.0	25	13	3.6	3.2	12	5	5.6	5.5	1.8
C-503	10.4	23	10	4.5	4.0	12	1.2	5.6	3.6	35.7
Hyflo Super-Cel	5.2	18	7	4.1	3.4	18	0.45	5.6	1.5	73.2
C-512	4.3	15	5	4.7	3.3	31				
Standard Super-Cel	3.1	14	3.5	4.9	2.4	50	0.22	5.6	0.49	91.3
Filter Cel	1.5	7.5	1.5	5.0	0.1	98				

[1] These values come from Johns Manville (1981).

[2] The influent and effluent turbidity values represent the average removal for all test runs performed per grade. Test runs 46 and 47 were not included in these calculations because of the increased influent turbidity concentrations.

[3] These data are from Table 11.

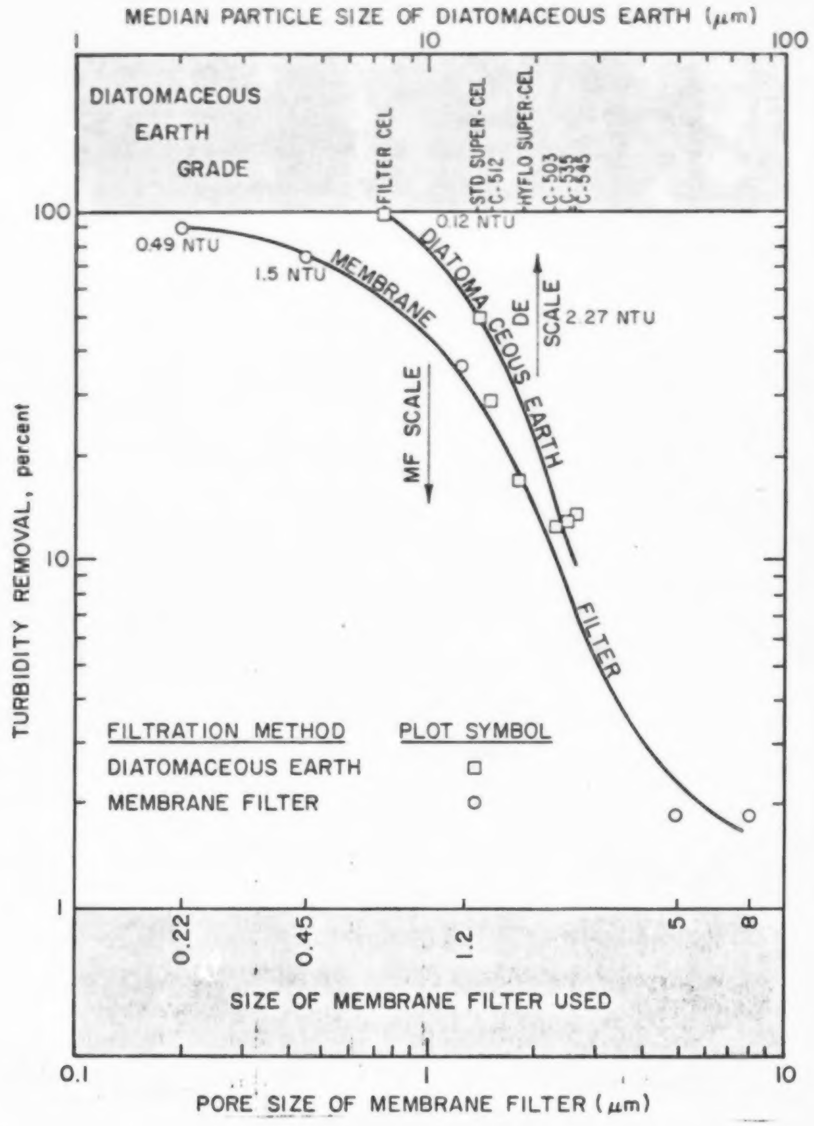

Figure 36. Comparison of percent turbidity removals, Horsetooth Reservoir water, by membrane filters of different sizes and diatomaceous earth of different grades.

the average pore size of diatomaceous earth grades 545, 535 and 503 is greater than 9 µm. It is also evident from the membrane tests that the majority of turbidity particles will pass an 8 µm membrane filter. These two sets of data side by side facilitate comparison of the roles of grade and effective membrane pore size in turbidity removal.

These same data, plotted in Figure 36, show the correlation of turbidity removal to diatomaceous earth median particle size and membrane filter pore size. From this, it may be inferred that similar percent removals of turbidity are due to the same pore sizes. For example, a 70 percent removal of turbidity would be affected by a 0.50 µm pore size membrane filter, and a 11 µm median particle size diatomaceous earth. It could also be inferred then that the corresponding effective pore size of the diatomaceous is due primarily to straining.

Giardia cyst and particle: Table 16 shows the removal percentages of *Giardia* cysts and particles for the four largest grades of diatomaceous earth tested. Testing of *Giardia* cyst removal was not done for the three smaller grades since cyst sized particles are removed by the larger grades and consequently will not pass the smaller grades.

Headloss: Table 16 shows that the headloss-grade relationship is not clear, except it does definitely increase sharply with the smaller grades. The latter is consistent with what is expected. The inconsistent results are due to the variation in turbidity, i.e. influent particle loading, during the various test runs. The largest variations occurred when different concentrations of *Giardia* cysts were added.

Hydraulic loading rate

Table 18 shows various hydraulic loading rates and the resultant percent removals of total coliform bacteria, standard plate count bacteria, *Giardia* cysts, turbidity, and particle counts for different grades of diatomaceous earth. Values shown are averages of data generated for all test runs for a given grade and at the hydraulic loading rate indicated. Hydraulic loading rates used were 2.44, 4.88, and 9.76 m/hr (1, 2, and 4 gpm/ft^2). This table was constructed from the raw data table in Table E-1 for thirty-nine test runs. The results of measurements in each test run were averaged for the first 90 to 100 minutes of filtration time and then weighted and averaged together by hydraulic loading rate.

Table 18 indicates generally that as hydraulic loading rate increases, the removal percentages of total coliform bacteria, standard plate count bacteria, and turbidity decrease, but the trends are not clear and data were not obtained for each grade at the three hydraulic loading rates. Thus the data do not warrant conclusive assertion. The removals of *Giardia* cysts were uniformly at 100 percent for all three hydraulic loading rates, with one exception, e.g. Run 41. Particle removal in the 6.35 to 12.67 micrometer size range did not seem to be affected by hydraulic loading rate. Also, it would be expected that as hydraulic loading rate increases the rate of pressure increase will rise. This is not discerned unequivocally, however, in Table 18.

Table 18. Effect of hydraulic loading rate on percent removals of dependent variables for different grades of diatomaceous earth. Data taken after 90 minutes of run time and averaged for all test runs for specified grade and hydraulic loading rate.

Grade	Hydraulic Loading Rate (m/hr)	No. of Test Runs	Average Rate of Pressure Increase (cm Hg/hr)	Total Coliform Bacteria Removal (%)	Standard Plate Count Bacteria Removal (%)	*Giardia* Cyst Removal (%)	Turbidity Removal (%)	Particle Removal 6.35 to 12.67 µm (%)
C-545	2.44	11	.47	35	53	>99	16	94
	4.88	3	.53	18	67	100	14	96
	9.76	2	1.3	31	44	100	13	95
C-535	2.44	1	0.0	62	64	100	11	97
	4.88	1	0.2	89	64	100	14	85
	9.76	0						
C-503	2.44	6	0.35	77	64	100	12	73
	4.88	3	0.30	60	64	100	14	97
	9.76	1	1.4	48	67	100	14	84
Hyflo Super-Cel	2.44	3	<.1	91	79	100	20	94
	4.88	1	0.10	100	98	100	12	98
	9.76	0						
C-512	2.44	2	0.55	95	76	ND	32	ND
	4.88	0						
	9.76	0						
Standard Super-Cel	2.44	3	2.44	99.9	98	ND	54	ND
	4.88	0						
	9.76	0						
Filter Cel	2.44	2	59	100	>99	ND	98	
	4.88	0						
	9.76	0						

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[1] Rate of pressure increase was not consistent with expectations because of differing characteristics of sewage and dog feces added for testing purposes.

Influent concentrations of dependent variables

This section describes results related to the effect of influent concentrations of total coliform bacteria, standard plate count bacteria, Giardia cysts, turbidity, and particle counts on the removal efficiencies of these variables. The general trend of the data indicates that removal percentages decrease with increasing influent concentrations.

Total coliform bacteria: Table 19 shows the effect of increasing influent total coliform bacteria concentrations on the total coliform bacteria removal percentage for each grade of diatomaceous earth tested. The data from five of the six grades tested indicated that removal percentage decreases with increasing influent total coliform concentrations. Table 20, constructed from data presented by J. V. Hunter et al. (1966), also shows this relationship.

Standard plate count bacteria: Table 21 shows the average influent and effluent concentrations and removal percentages of standard plate count bacteria measurements in order of decreasing influent standard plate count bacteria concentrations. For four of the six diatomaceous earth grades tested, the results indicate that removal percentage decreases with increasing influent standard plate count bacteria concentrations. The remaining two grades, Standard Super-Cel and Filter-Cel had removal percentages greater than 96 percent for all concentrations tested.

Giardia cysts: Table 22 shows that diatomaceous earth filtration test runs with influent Giardia cyst concentrations ranging from 770 to 33,600 cysts/liter all had Giardia cyst removal percentages greater than 99.9 percent. Giardia cysts were detected only in the diatomaceous earth filtrate from one test run which had an influent Giardia cyst concentration of 33,600 cysts/liter, the highest cyst loading applied to the filter. The next highest Giardia cyst concentration tested, 10,000 cysts/liter, did not cause cyst to breakthrough into the effluent.

Turbidity: Table 23 shows the average influent and effluent turbidity concentrations and turbidity removal percentages for ten test runs, with run lengths of 330 minutes or longer. Testing with five grades of diatomaceous earth indicates that turbidity removal increases with finer grades of diatomaceous earth. One water, i.e., Horsetooth Reservoir, was used. There was not sufficient range of turbidity in this water to discern any functional relationship between turbidity removal and turbidity level.

Particles: Table 12 shows that the raw water particle counts in the 6.35 to 12.70 μm size range were higher when influent Giardia cyst concentrations were greater than 100 cysts/liter. These higher influent particle concentrations showed no effect on particle removal percentages.

Headloss and run-length

All diatomaceous earth filtration test runs were conducted with a bodyfeed/turbidity ratio which caused a linear rise in headloss, when plotted against time. The results in this section show that headloss did not greatly

Table 19. Effect of total coliform bacteria concentration on total coliform bacteria removal by diatomaceous earth filtration. Hydraulic loading rate maintained at 2.44 m/hr.

TEST IDENTIFICATION		TEST CONDITIONS			RESULTS	
Date	Run No.	Grade	Duration of Test Run (min)	Average Influent Concentration[1] (No./100 ml)	Average Effluent Concentration[1] (No./100 ml)	Percent Removal (%)
7/30/82	28	C-545	120	35,000	21,500	39
7/27/82	20		90	30,000	16,500	45
10/14/82	46		120	9,600	3,425	64
7/14/82	14		90	56	13	77
7/28/82	25	C-503	90	36,000	9,800	73
7/27/82	23		90	6,100	1,900	69
8/6/82	32		90	3,850	1,350	65
7/13/82	12		90	28	<1	96
8/5/82	31	Hyflo Super-Cel	90	4000	520	87
7/12/82	10		90	39	<1	97
8/11/82	35	C-512	330	2380	71	97
8/9/82	33		330	1050	<12	>99
8/18/82	38	Standard Super-Cel	325	32,500	58	99.8
8/4/82	30		330	6,100	<1.7	99.9
8/10/82	34	Filter Cel	115	855	<1	99.9
8/11/82	36		120	640	<1	99.8

[1] These values were measured in the first 120 minutes of runtime.

Table 20. Total coliform removal by diatomaceous earth filtration with various influent coliform concentrations.[1]

Grade	Influent Conc. (no./100 ml)	Average Effluent Conc. (no./100 ml)	Removal (%)
Standard Super-Cel	15	<1	>99.9
	225	<1	>99.9
	1900	<1	>99.9
	36,000	0.2	>99.9
Celite 512	50	0.4	99
	136	1.7	99
	150	2.9	99
	175	4.5	97
	485	1.3	>99
	570	3.8	99
	825	18.4	98
	2,500	187.5	98
	9,950	382.5	96

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[1] This table was constructed with data developed by J. V. Hunter et al. and reported in "Coliform Organism Removals by Diatomite Filtration," JAWWA, 74:9 (September 1966), 1160-1169.

Table 21. Effect of standard plate count bacteria concentration on standard plate count bacteria removal by diatomaceous earth filtration. Hydraulic loading rate is 2.44 m/hr.

TEST IDENTIFICATION		TEST CONDITIONS			RESULTS	
Date	Run No.	Grade	Duration of Test Run (min)	Average Influent Concentration[1] (No./1 ml)	Average Effluent Concentration[1] (No./1 ml)	Percent Removal (%)
7/30/82	28	C-545	120	79,000	29,900	62
7/27/82	20		90	44,500	16,300	63
10/14/82	46		120	17,550	8,825	50
7/26/82	18		90	9,800	2,465	75
7/14/82	19		90	1,765	298	83
7/28/82	25	C-503	90	75,450	22,900	70
10/21/82	47		120	9,400	4,030	57
8/6/82	32		90	9,000	2,890	68
7/27/82	23		90	7,300	2,700	63
7/13/82	11		90	2,430	59	98
8/5/82	31	Hyflo Super-Cel	90	8600	4800	44
7/12/82	9		90	1945	121	94
8/9/812	33	C-512	330	4250	946	78
8/11/82	35		330	3600	736	80
8/18/82	38	Standard Super-Cel	325	2,955,000	66	>99.9
8/4/82	30		330	9,250	337	96
8/19/82	39		330	6,200	77	98.8
8/10/82	34	Filter Cel	115	3950	<2	>99.9
8/11/82	36		120	990	3	99.7

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[1] These values were measured in the first 120 minutes of runtime.

Table 22. Effect of influent Giardia cyst concentrations on Giardia cyst removal percentages.

TEST IDENTIFICATION		TEST CONDITIONS			RESULTS	
Date	Run No.	Grade	Filt. Rate (m/hr)	Giardia Cyst Concentration Added to Feed Water (cysts/liter)	No. of Cysts Detected in Effluent Sample (No.)	Giardia Cyst[1/] Percent Removal (%)
7/30/82	28	C-545	2.44	770	<1	>99.958
11/18/82	49	C-545	2.44	2,467	<1	>99.999
10/ 5/82	43	C-545	2.44	5,460	<1	>99.998
10/ 7/82	44	C-545	2.44	5,460	<1	>99.998
10/12/82	45	C-545	2.44	8,850	<1	>99.999
9/30/82	42	C-545	2.44	10,000	<1	>99.998
8/26/82	41	C-545	2.44	33,600	1,700	99.925

[1/] Based on membrane filter sampling recovery efficiency (see Table 13).

Table 23. Effect of influent turbidity on average turbidity removal for five diatomaceous earth grades. Data obtained from Table 10 selecting five-hour test runs using water from Horsetooth Reservoir.

TEST IDENTIFICATION		TEST CONDITIONS			RESULTS	
Date	Run No.	Grade	Duration of Test Run (min)	Average Influent Turbidity (NTU)	Average Effluent Turbidity (NTU)	Percent Removal (%)
10/14/82	46	C-545	360	7.68	6.8	11
7/30/82	28	C-545	370	4.60	3.8	17
10/21/82	47	C-503	330	7.6	7.0	8
8/6/82	32	C-503	330	4.6	4.1	11
8/5/82	31	Hyflo[1]	330	4.6	3.8	18
8/3/82	29	Hyflo	330	4.57	3.6	20
8/9/82	33	C-512	330	4.9	3.2	34
8/11/82	35	C-512	330	4.6	3.3	28
8/19/82	39	Standard[2]	330	5.1	2.5	50
8/18/82	38	Standard	355	5.0	2.5	49
8/4/82	30	Standard	330	4.5	2.3	50

[1] Hyflo Super-Cel

[2] Standard Super-Cel

Table 24. Particle analyses for different rates of differential pressure increase across a diatomaceous earth filter for particle size of 2.5 to 12.7 µm. Diatomaceous earth grade was Standard Super-Cel.

Influent Particle Concentration (No./ml)	Effluent Particle Concentration (No./ml)	Rate of Increase in Differential Pressure (cm Hg/min)
47	428	0.35
7572	69	0.06

affect the removal efficiency of the dependent variables but that run length did affect bacteria removal.

Headloss did not appear to affect the removal of total coliform bacteria, standard plate count bacteria, turbidity, or Giardia cysts. The highest headloss tested on diatomaceous earth Grade C-545, which was 72.8 feet of water, did not cause Giardia cysts to break through into the effluent sample. Even tests with high rates of pressure increase, e.g., 0.46-2.53 cmHg/hr for Grade C-545, did not seem to affect the removal of these dependent variables.

Particle counts: The rate of increase in headloss across the filter cake was found to have marked effect on effluent particle counts. Table 24 illustrates this by comparing particle counts for a high rate of pressure increase, e.g. 0.35 cmHg/min, to particle counts for a low rate, e.g. 0.06 cmHg/min. At the high rate the particle concentration found in the effluent was 428/ml, despite the low influent concentration of 47/ml. By contrast, for the low rate of headloss increase, the effluent particle concentration was only 69/ml, even with an influent concentration of 7572/ml. We believe this is caused by attrition of the diatomaceous earth filter cake through collapse of the particle bridges at the septum and their release through the septum. The Standard Super-Cel grade of diatomaceous earth was used in the tests, which has a D_{10} size of 3.1 µm and D_{60} of 11.1 µm. This is within the size range noted. Complete data for the tests is given in Appendix B.

Run time: A 16-hour diatomaceous earth filtration test was performed to determine if run length would cause Giardia cysts to breakthrough the filter. The sixteen hours was selected as a reasonable time to allow for conditions to be stabilized. After 16 hours of filtration time over which an average of 2,467 cysts/liter were intermittently fed to the diatomaceous earth filter, zero cysts were detected in the effluent sample.

Table 25 shows the total coliform removal, as a function of increasing filtration time (up to 370 minutes), for eight diatomaceous earth filtration test runs. Seven of the tests indicate that total coliform bacteria removal percentages decrease with increasing run length. The raw data in Table E-1 show that standard plate count bacteria removals also tends to decrease with time.

Temperature

Table 26 compares percentage removals for Giardia cysts, total coliform bacteria, standard plate count bacteria, turbidity, and particle counts between test runs at 5°C and 13°C. Removals of Giardia cysts were 100 percent (reported in Table 26 at detection limit levels) for all conditions. Concentrations of the other variables happened to be higher at the same time temperatures were lowered. So while Table 26 shows that removal percentages are lower at 5°C than for 13°C for total coliform bacteria, standard plate count bacteria, and particles (and higher for turbidity), one cannot conclude the change is due to temperature, since it has been shown that removal for these parameters decreases with increased influent concentrations.

Table 25. Effect of run time on total coliform bacteria removal for various grades of diatomaceous earth. Calculated from data in Table E-1.

Run No.	28	46	32	47	31	33	35	30
Grade of Diatomaceous Earth	C-545	C-545	C-503	C-503	Hyflo Super-Cel	C-512	C-512	Standard Super-Cel
Time (min)	Removal %	Removal %	Removal %	Removal %	Removal %	Removal %	Removal %	Removal %
30	56		78	87	89	>99	99	>99.9
60		77		84				
90			62		85	>99	98	>99.9
120	18	67		80				
150			55		82	>99	98	>99.9
180		75		76				
210	3		57	78	81	>99	96	>99.9
240		73						
270	29		64	80	79	>99	95	>99.9
300		67						
330			93	79	80	98	95	>99.9
360		67						
370	18							
Average Influent Total Coliform Concentration (No./100 ml)	34,000	12,167	4,450	13,500	4,000	1,050	2,380	6,100

Table 26. Effect of temperature on removal percentages of dependent variables.

Date	Grade of D.E.	Filt. Rate (m/hr)	No. of Tests	Temp. (°C)	Total Coliform		Standard Plate Count		*Giardia* Cysts		Turbidity		Particle Counts	
					Infl. (No./ 100 ml)	Removal (%)	Infl. (No./ 100 ml)	Removal (%)	Infl. (cysts/ liter)	Removal (%)	Infl. (NTU)	Removal (%)	Infl. (No./ 10 ml)	Removal (%)
5/6/83	C-545	2.44	1	3.5	3500	71	6000	83	7400	>99.9	2.4	39	ND[2]	ND
7/4/82	C-545	2.44	1	5	55	77	1765	83	100	99.3	3.3	6	831	96
4/23/82	C-545	2.44	1	9	7000	77	26500	87	1650	99.4	32.0	77	ND	ND
7/26/82	C-545	2.44	1	13	ND	ND	9800	75	100	99.5	4.2	14	776	90
5/6/83	C-545	4.88	1	3.5	2500	42	1075	26	500	99.9	0.55	22	ND	ND
7/14/83	C-545	4.88	1	5	55	64	1765	74	100	99.6	3.4	4	669	96
7/28/82	C-545	4.88	1	13	ND	ND	9900	30	100	99.7	4.2	14	776	95
7/13/82	C-503	2.44	1	5	27	96	2430	98	100	99.7	3.5	6	989	99
7/27/82	C-503	2.44	1	13	6100	69	7300	63	100	ND	4.2	15	865	81
7/13/82	C-503	4.88	1	5	27	96	2430	94	100	99.5	3.6	8	ND	ND
7/27/82	C-503	4.88	1	13	5450	75	8250	67	100	99.6	4.2	14	865	99
7/12/82	Hyflo	2.44	1	5	39	97	1945	94	100	99.5	3.7	20	732	78
8/5/82	Hyflo	2.44	1	13	4000	83	9050	65	0	ND	4.6	18	ND	ND

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[1] Determined by membrane sampling recovery efficiency (see Table 3).

[2] No measurement taken for this test run.

Alum-coated diatomaceous earth

This section describes the results of ten test runs in which alum-coated diatomaceous earth was used. Both precoat and bodyfeed diatomaceous earth slurries were treated in the same manner. Table 10 shows the average removal percentages and average influent and effluent concentrations of total coliform bacteria, standard plate count bacteria, and turbidity for these 10 tests (run numbers 48 to 58). All measured data taken during each test run are given in Table E-1.

Removal of dependent variables: Table 27, derived from Table 10, shows the average removal percentages of total coliform standard plate count bacteria, and turbidity for alum-coated diatomaceous earth grades C-545 and C-503. This table shows that removal percentages for: 1) total coliform bacteria ranged from 96 to 99.9 percent, 2) standard plate count bacteria ranged from 79 to 99 percent, and 3) turbidity ranged from 66 to 98.8 percent. For comparison, Table 27 also shows removal percentages for the two grades without alum coating is dramatically less.

The data in Table 27 also show that C-503, the smaller grade size of diatomaceous earth, requires a higher alum concentration than C-545 to obtain the same bacteria and turbidity removal. The removal percentages of total coliform bacteria, standard plate count bacteria, and turbidity for alum-coated C-545 (26.0 μm median particle size) having .05 alum-diatomaceous earth ratio are higher than any of the respective removal percentages for alum-coated C-503 (23.0 μm median particle size) having .05 alum-diatomaceous earth ratio, using the same 25 ppm bodyfeed concentration. Previous work by Burns et al. (1970) corroborates this observation; they found that the chemical concentration needed to coat diatomite is a function of diatomite particle surface area.

Figure 37 shows effluent turbidity plotted against run time for six filtration test runs using alum-coated diatomaceous earth. Data from Table E-1 were used to plot these curves. Each of these curves shows that the effluent turbidity rises, peaks, and then decreases or levels off. The initial low turbidity is caused possibly by the attachment of particles to the fresh alum-coated precoat layer. Based upon this premise, the number of available attachment sites in the precoat decreases, resulting in a rise in turbidity. Then the alum-coated bodyfeed addition provides enough particle attachment sites to cause the removal to improve again. The final effluent turbidity value depends on the alum concentration, bodyfeed addition, water characteristics and diatomaceous earth particle size. The curves show the effect of alum-diatomaceous earth ratio; higher ratios cause lower effluent turbidities. Results for Run 53 show that higher bodyfeed causes lower turbidities.

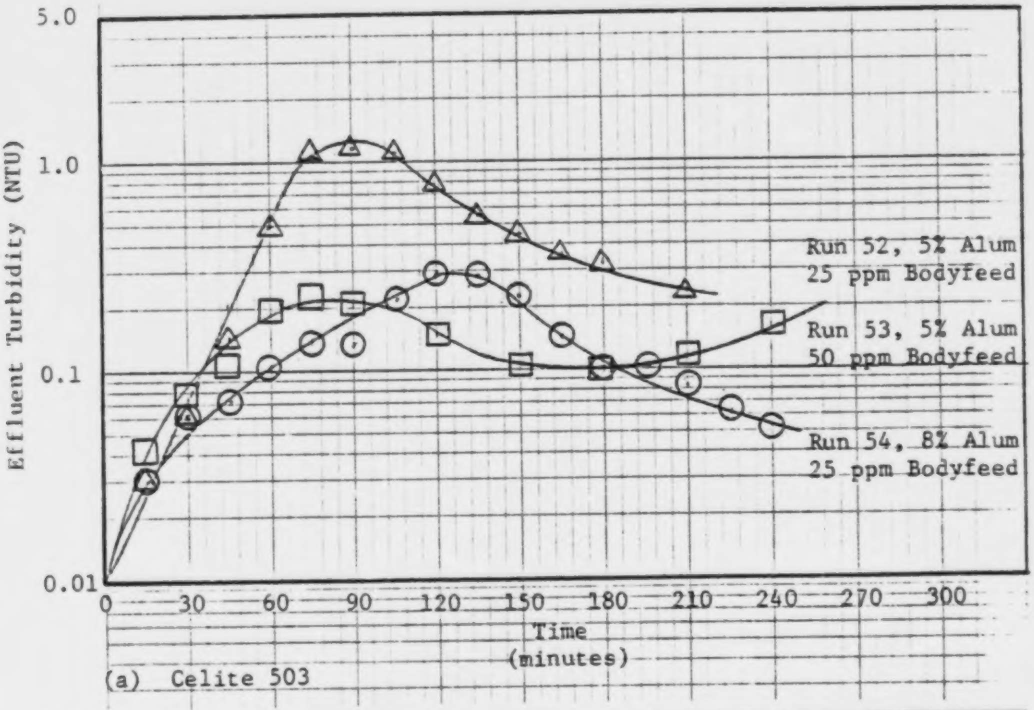
Table 28 shows the effect of using no alum on either precoat or bodyfeed compared with using it on the precoat only, on the bodyfeed only, and on both the precoat and the bodyfeed. Figure 38 shows these data plotted against run time. The plots show that without alum, filtration with C-545 removes only about 10 percent of the influent turbidity, but that the use of alum on precoat only, bodyfeed only, and both precoat and bodyfeed, has increasing

Table 27. Removal percentages of total coliform bacteria, standard plate count bacteria, and turbidity for diatomaceous earth grades C-545 and C-503 coated at various alum concentrations. Data obtained from Table 10.

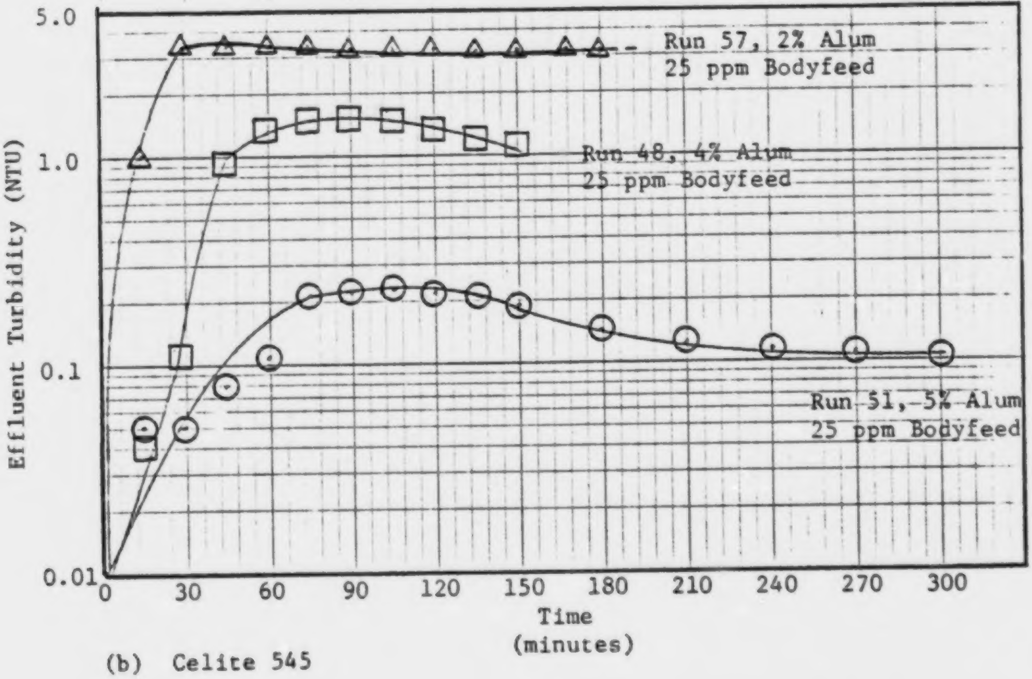
Grade		AVERAGE REMOVALS		
		Total Coliform (%)	Standard Plate Count (%)	Turbidity (%)
C-545	2	-	-	66.11
	4	99.02	95.02	86.41
	5	99.86	98.56	98.38
C-503	5[1]	98.01	79.31	79.06
	5	99.56	93.25	94.41
	5[2]	96.33	99.57	98.61
	8	99.83	99.52	98.80

[1] Bodyfeed concentration was increased to 50 ppm after 3 hours of testing at 25 ppm

[2] Bodyfeed concentration 50 ppm, all other bodyfeed rates were 25 ppm



(a) Celite 503



(b) Celite 545

Figure 37. Effluent turbidity versus test run time for: (a) Celite 503 and (b) Celite 545.

Table 28. Turbidity removal as affected by use of alum on both precoat and bodyfeed, on precoat alone, with no bodyfeed, on bodyfeed alone with no alum on precoat, and without alum. Taken from data in Table E-1.

	0 Alum-DE Ratio for bodyfeed and precoat Run 46, Influent 2.68 NTU			.05 Alum-DE Ratio For precoat only; no bodyfeed is used Run 55, Influent 10.0 NTU			.05 Alum-DE Ratio for bodyfeed only Run 58, Influent 9.2 NTU			.05 Alum DE Ratio For both precoat and bodyfeed Run 51, Influent 9.4 NTU			Calculated 55 & 58 combined .05 Alum-DE Ratio	
Time (min)	Turb. (NTU)	Removal (%)	Remain. (%)	Turb. (NTU)	Removal (%)	Remain. (%)	Turb. (NTU)	Removal (%)	Remain. (%)	Turb. (NTU)	Removal (%)	Remain. (%)	Removal (%)	Remain. (%)
0														
15				.10	99	1	7.7	16	84	.05	99.5	0.5	99.2	0.8
30				1.12	88	11	6.7	22	73	.05	99.5	0.5	91.5	8.5
45				2.2	78	22	5.9	36	64	.08	99.2	0.8	85.3	14.7
60	7.0	9.10	90.90	2.8	72	28	5.2	44	56	.11	98.8	1.2	83.5	16.5
75				3.2	68	32	4.7	49	51	.21	97.8	2.2	83.0	17.0
90				3.4	66	34	4.3	53	47	.23	97.6	2.4	84.5	16.5
105				3.9	61	39	3.4	63	37	.25	97.3	2.7	85.0	15.0
120	6.8	10.53	89.47	4.0	60	40	3.0	67	33	.23	97.6	2.4	86.4	13.6
135				4.0	60	40	2.8	70	30	.21	97.8	2.2	87.3	12.7
150				4.1	59	41	2.5	73	27	.19	97.8	2.0	88.4	11.6
165				4.2	58	42	2.3	75	25				89.1	10.9
180	6.7	12.99	87.01	4.3	57	43	2.0	78	22	.16	98.3	1.7	90.3	9.7
195				4.4	56	44	1.7	81	19				91.5	8.5
210				4.0	60	40	1.51	84	16	.14	98.5	1.5	93.2	6.8
225				4.3	57	43	1.33	85	15				93.5	6.5
240	6.8	11.69	88.31	4.5	55	45	1.25	86	14	.13	98.6	1.4	93.6	6.4
255							1.17	87	13					
270							1.22	87	13	.12	98.7	1.3		
285							1.22	87	13					
300	6.8	11.69	88.31				1.20	87	13	.12	98.7	1.3		

Run 51 has 90 gm precoat and 25 mg/L bodyfeed, Run 55 has 90 gm precoat and no bodyfeed.
Runs 58 and 46 have 90 gm precoat and 25 mg/L bodyfeed.

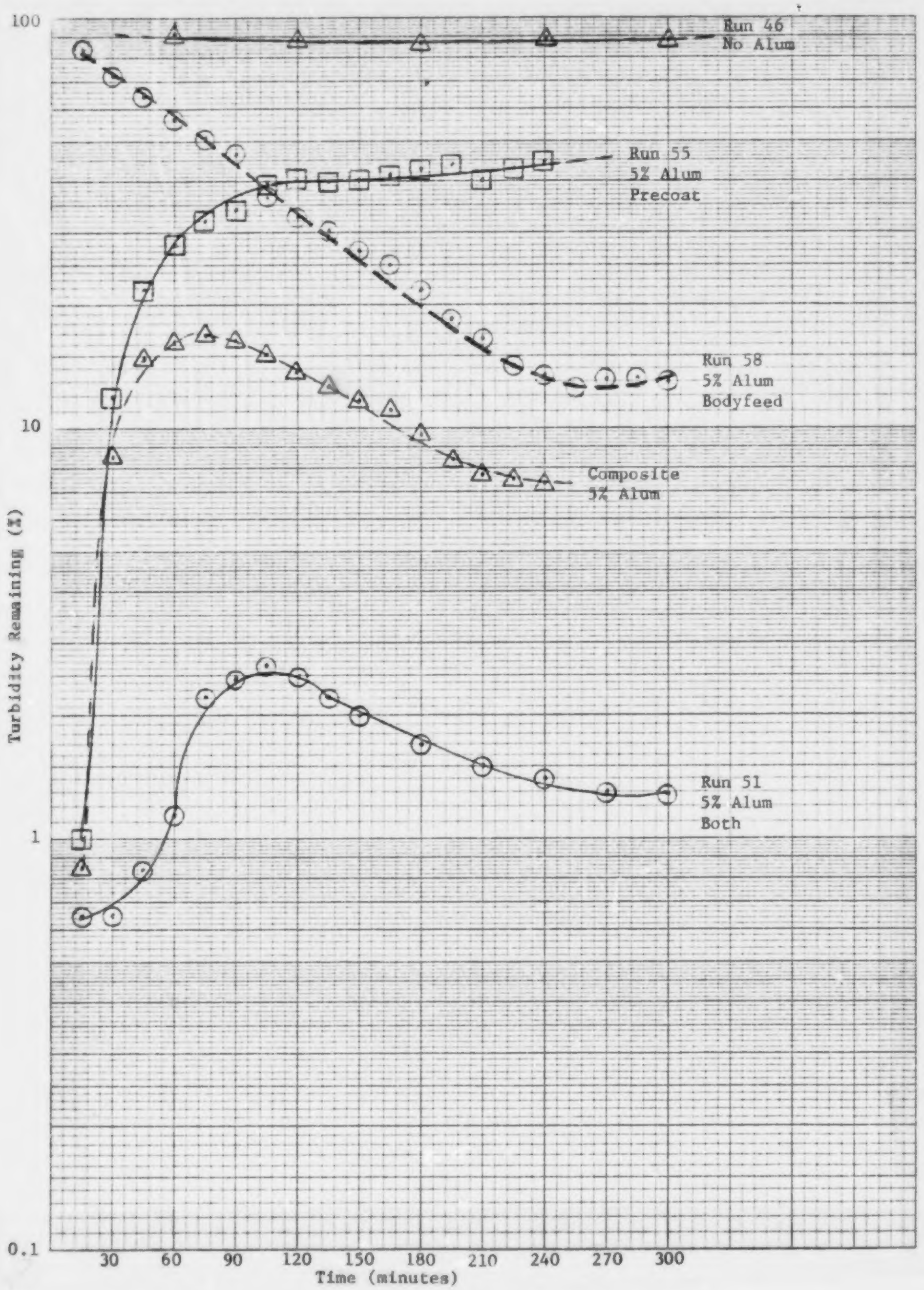


Figure 38. Turbidity removal by diatomaceous earth filtration, grade C-545, as affected by use of alum on both pre-coat and bodyfeed, on pre-coat alone, on bodyfeed alone, and without alum. Plotted from Table 28.

strong influence on percent turbidity remaining. Using alum on both precoat and bodyfeed can produce a product water having turbidity near 1 NTU using water from Horsetooth Reservoir.

Run 51 in Figure 38 shows a typical experimental curve of percent turbidity remaining vs. time when alum is used with both precoat and bodyfeed. The percent turbidity remaining increases and then declines to a steady-state level as run time continues. Without alum the percent turbidity remaining curve will rise continuously with time. The percent turbidity remaining curve of Run 51 can be simulated by compositing Run 55 with Run 58, i.e.

$$\begin{array}{c}\text{Calculated percent turbidity}\\ \text{removal for alum precoat}\\ \text{+ alum bodyfeed}\end{array} = \begin{array}{c}\text{Turbidity remaining}\\ \text{for alum precoat,}\\ \text{Run 55}\end{array} \times \begin{array}{c}\text{Percent turbidity}\\ \text{removal for alum}\\ \text{bodyfeed, Run 58}\end{array}$$

$$+ \begin{array}{c}\text{Percent turbidity removal}\\ \text{for alum precoat, Run 55}\end{array}$$

This shows that the initial cause of turbidity removal is all due to the effect of precoat. As the run continues the effect of the precoat layer declines and the role of bodyfeed increases. This is illustrated by Runs 55 and 58, respectively, and by the calculated composite of these two runs, and by the experimental composite, Run 51.

As a matter of interest, displacement of the calculated combined curve from the experimental curve, Run 51, is due to the different waters used during the different test runs, as the absolute results seem to be nominally sensitive to the characteristics of the raw water. This notwithstanding, the similarity of the trends is demonstrated.

Table 29 shows the total coliform bacteria removal with time for six test runs using alum-coated diatomaceous earth. This table indicates that total coliform bacteria is essentially constant with time. The role of bodyfeed must be the operative parameter in maintaining the constant removal with time, based upon the effects of precoat and bodyfeed noted in Figure 38.

Headloss: Figures 39 and 40 for grades C-545 and C-503, respectively, show headloss versus run time for the seven diatomaceous earth test runs in which alum addition was used. These figures indicate that linear headloss-run time relationships can be achieved with low alum concentrations. Higher alum-diatomaceous earth ratios may cause the diatomite particles to coagulate and bridge, closing the pores in the filter cake.

Table 29. Total coliform bacteria removal versus time for alum coated diatomaceous earth.

Grade of Diatomaceous Earth	Run 48 C-545 .04 Alum-DE	Run 50 C-503 .05 Alum-DE	Run 51 C-545 .05 Alum-DE	Run 52 C-503 .05 Alum-DE	Run 53 C-503 .05 Alum-De	Run 54 C-503 .08 Alum-DE
Time (min)						
15		99.9	>99.9			
30	99.8	99.9	>99.9	99.9		
60	99.1	99.7	99.9	99.8		
90	98.8	99.9	99.9	99.4	>95.9	
120	98.2	97.9	99.8	99.4		99.8
150	98.2	96.7	99.9			
180		96.9		99.3		99.7
210		97.7	99.7			
240		97.2			99.7	99.9
270		95.7				
300		97.7	98.8		99.6	
Average Removal (%)	98.8	98.1	>99.7	99.6	>98.4	99.8
Average Influent Total Coliform Conc. (No./100ml)	3450	4975	5800	6950	6150	7100

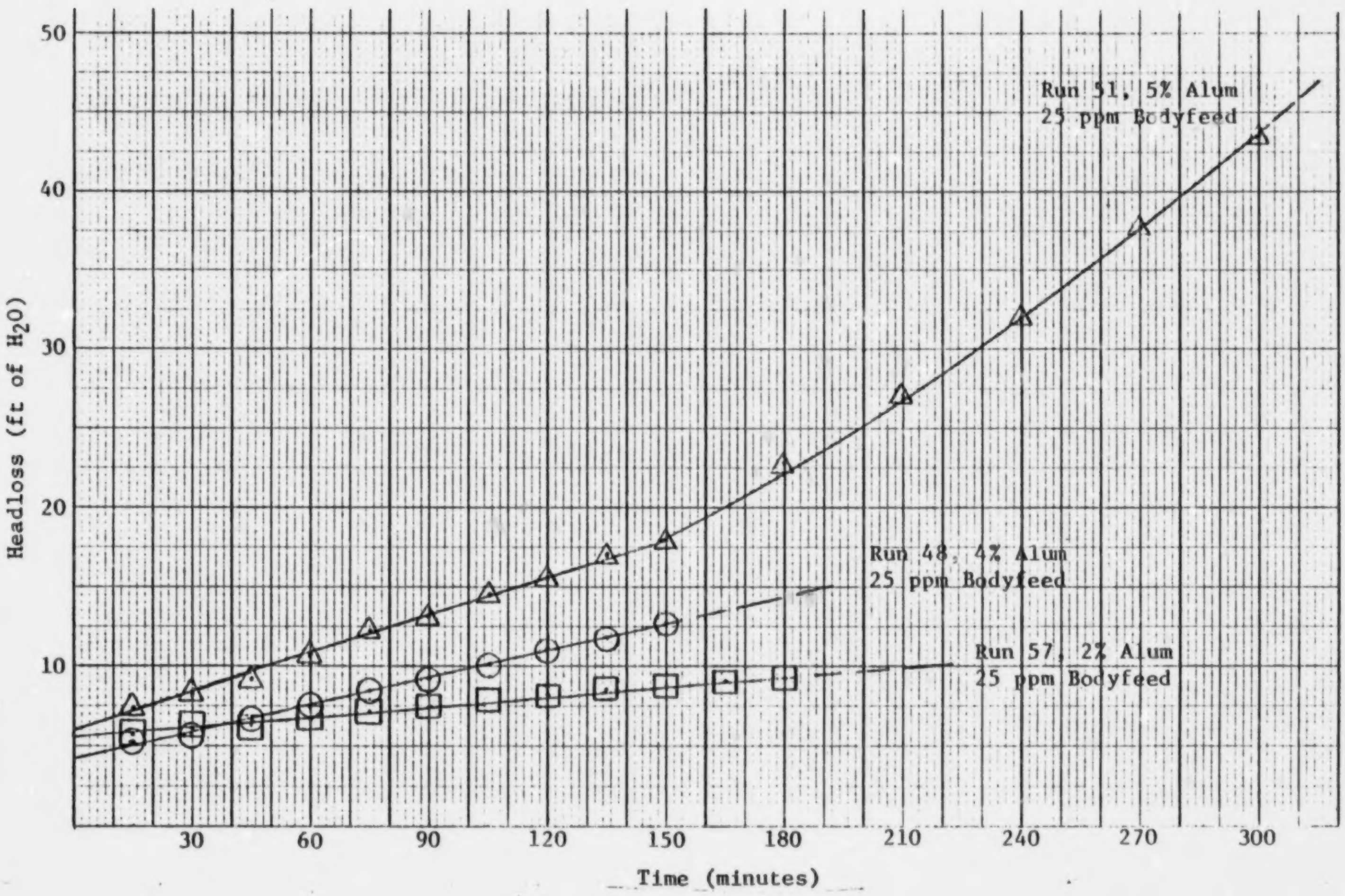


Figure 39. Headloss in feet of water versus run length for alum coated C-545 test runs.

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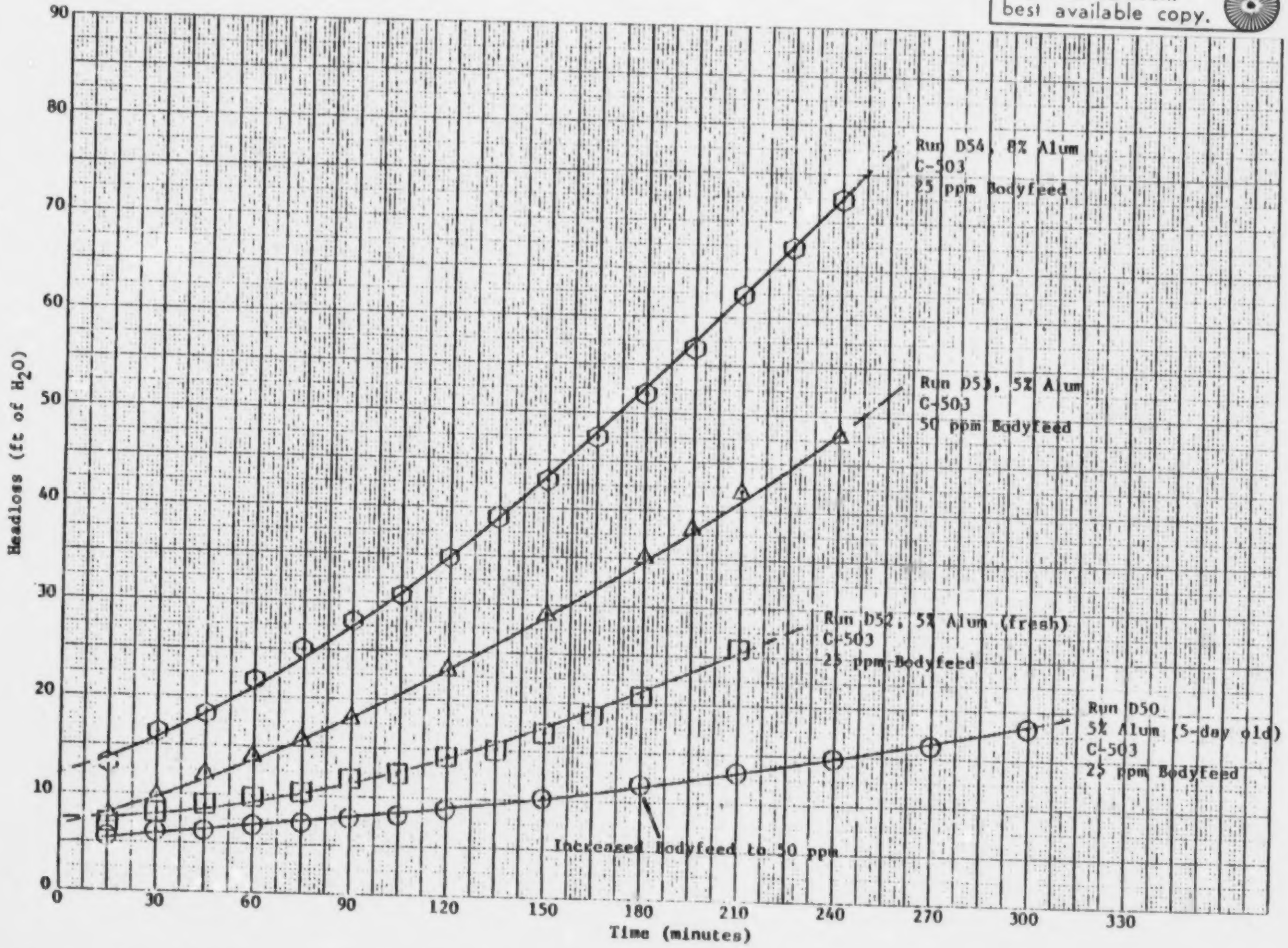

Figure 40. Headloss in feet of water versus run length for alum coated C-503 test runs.

SECTION 6

FIELD TESTING

Nature of Investigation

In April and May 1983, field testing was performed at two locations to complete research on the removal of Giardia cysts by diatomaceous earth filtration. The purpose of this testing was to verify laboratory results obtained during February 1982 through February 1983, and to test the diatomaceous earth filtration process used in laboratory testing under ambient water conditions found in the field.

The scope of this testing included: one grade of diatomaceous earth (C-545-17 µm median pore size), hydraulic loading rates of 2.44, 4.88, and 9.76 m/m (1, 2, and 4 gpm/ft^2), ambient water conditions which provided a variation in temperature, turbidity, and chemical composition, and influent Giardia cyst concentrations ranging from 500 to 7,400 cysts/liter.

The field testing strategy was to set up the pilot plant identical to laboratory applications on-site at two different field locations. The experimental stragegy was designed to test C-545 water treatment grade of diatomaceous earth under various operating conditions to ascertain whether it is an effective barrier for the removal of Giardia cysts under a wide range of operating conditions.

Site Locations

Fort Collins Test Site

Testing in April 1983 was done adjacent to the Cache la Poudre River. The river is shown in Figures 41 and 42, at the site of Fort Collins Water Treatment Plant No. 1 where the testing was done. Two test runs were completed at this site. The first test occurred before spring runoff while the river turbidity was below 1.5 NTU. Figure 42 indicates the low flow condition of the river during this test run.

The second test run conducted at this site occurred during spring runoff. Figure 43 shows the higher river flow during this test, in which the turbidity was 32 NTU.

The pilot plant was set up outdoors, as shown in Figure 44, at the Fort Collins Water Treatment Plant No. 1. The water used for experimentation at this site was taken from the sand trap basin at the head of the plant. The effluent from the pilot plant was chlorinated, dechlorinated, and then

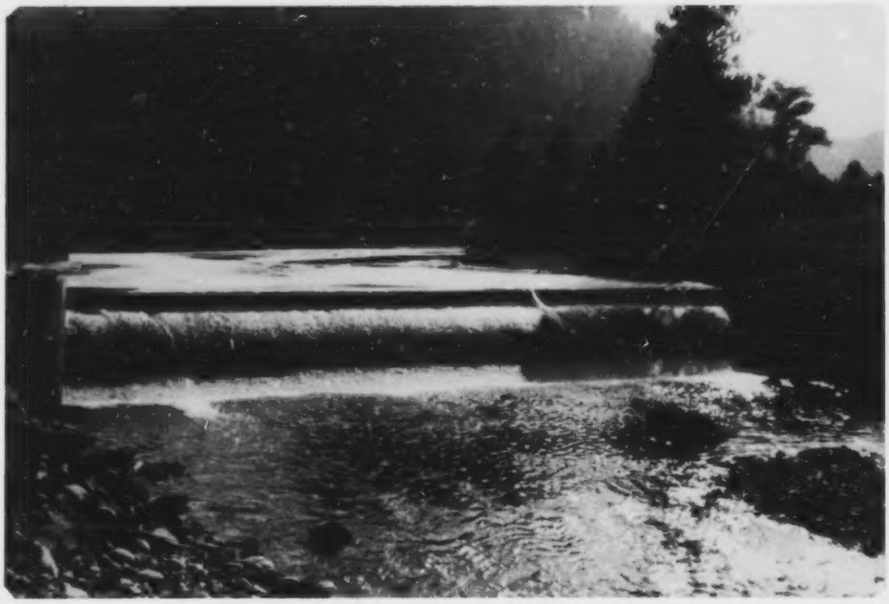

Figure 41. Cache la Poudre River Diversion point for Fort Collins Water Treatment Plant No. 1.

Figure 42. Cache la Poudre River during first field test run.

Figure 43. Cache la Poudre River during test run conducted after beginning of snow melt.

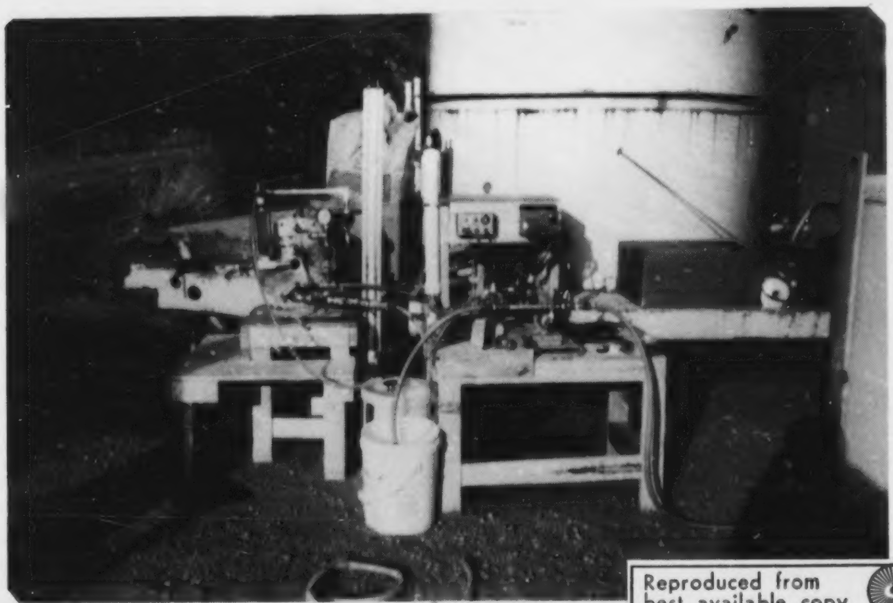

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Figure 44. Diatomaceous earth filtration pilot plant located at Fort Collins Water Treatment Plant No. 1.

released into the overflow box structure which receives the excess diverted water before it reenters the river.

Dillon Test Site

Figure 45 shows the Dillon Water Treatment Plant, the second field testing site which was used during May 1983. This water plant treats water from Straight and Laskey Creeks. These creeks carry snowmelt from the areas mountains above 3,000 meters and provide low temperature and low turbidity water year round. The pilot plant was set up indoors at this location as shown in Figure 46.

Figure 47 shows the plant's raw water intake line to which a garden hose was connected to fill the 700 liter feed tank used in the diatomaceous earth pilot plant testing. The effluent stream from the pilot plant was chlorinated, dechlorinated, and then released into the plants floor drains which led to a settling/holding pond.

Quality Control Procedures

Procedures for quality control were carried through for the field testing, as during laboratory work. Some additional procedures were necessary during the field work, however, which are described in the following paragraphs.

Before start-up

The diatomaceous earth filter unit was disassembled to seal the manifold O-rings before operation at each site. To ensure that no leaks existed in the filtration system, a precoat of Filter-Cel was applied to the diatomaceous earth filter and a slurry of coliform bacteria was filtered through the system. The effluent was sampled and tested for the presence of coliform bacteria by the membrane filter technique. Figures 48 and 49 show the disassembled filter unit and sealing the septum manifold prior to operation, respectively.

Precautionary procedures during testing

While our testing was accomplished under such conditions that cross contamination with the water treatment plants was not likely, additional precautions were taken. In addition, the operators at the two host plants were encouraged to oversee the diatomaceous earth pilot plant operations.

The precautions taken include attention to location of the pilot plant testing within the site area, to possibilities of influent line cross connections, and to disinfection of the pilot plant effluent stream and backwash water. The testing location was chosen so that it was physically remote from possible areas where cross-contamination could occur. The raw water feed tank was filled by a hose which was removed from the feed tank prior to the addition of the test materials comprised of primary effluent sewage and *Giardia* cysts. Figure 50 shows the batch addition of *Giardia* cyst concentrate to the filled raw water feed tank. Then, even though these

DILLON
WATER
PLANT

Figure 45. The second field testing site, the Dillon Water Treatment Plant.

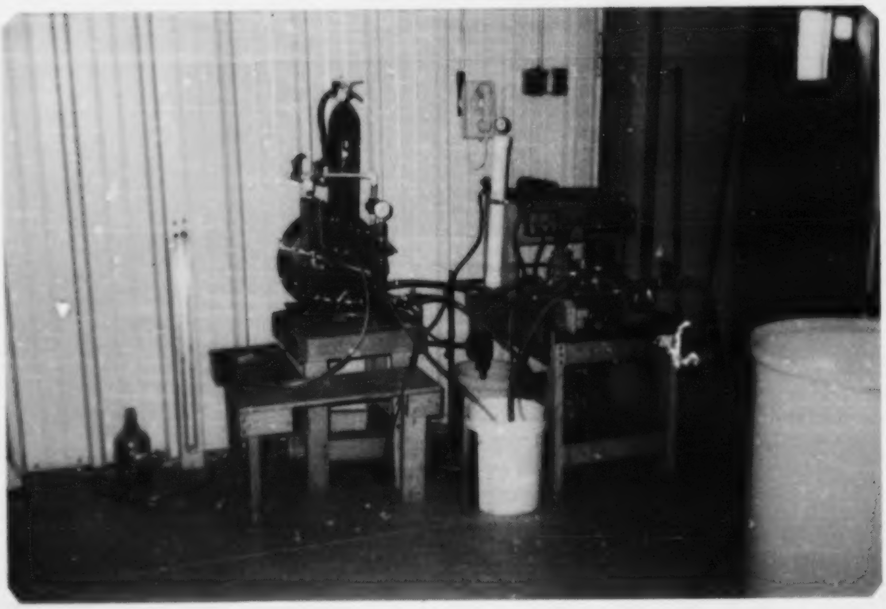

Figure 46. Pilot plant on location at the Dillon Water Treatment Plant.

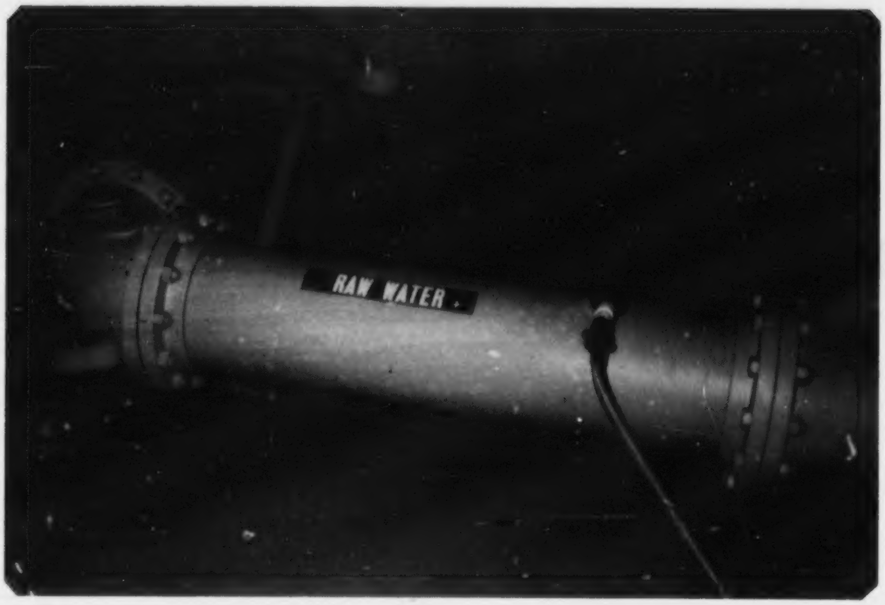

Figure 47. The Dillon Water Treatment Plant raw water feed line.

organisms were removed, presumably, during the testing process, all of the effluent streams from the diatomaceous earth pilot plant were decontaminated prior to release. Three two hundred-liter tanks shown in Figure 51 were used to contain the effluent streams from the pilot plant. Enough household bleach (sodium hypochlorite) was added to superchlorinate these containers to produce a 25 mg/L chlorine residual. After approximately forty minutes of detention time, sodium thiosulfate was added in stochiometric proportions to the chlorinated holding tanks to dechlorinate the effluent water prior to release. Furthermore, all backwash water used to remove the spent filter cake from the septum of the diatomaceous earth filter unit was collected in a 50 liter container. When testing was performed at the Fort Collins Water Treatment Plant, the backwash water was superchlorinated and then taken offsite, back to the Engineering Research Center at Colorado State University, for disposal. At the Dillon Water Treatment Plant, the backwash water was superchlorinated for twenty-four hours and then dechlorinated prior to release to the solids disposal ponds.

Extra precautions were taken also during the sample handling procedures to avoid any possibilities of water plant contamination. The Giardia cyst concentrate jar and the primary sewage effluent jar are shown in Figure 52. These jars along with distilled washwater and effluent sample bottles were kept refrigerated, as shown in Figure 53.

The effluent sampling of Giardia cysts was also performed with caution. A stainless steel membrane filter holder, shown in Figure 54 was used along with a 293 mm diameter, 5 μm pore size polycarbonate filter to collect Giardia cysts.

Figure 48. The disassembled filter unit.

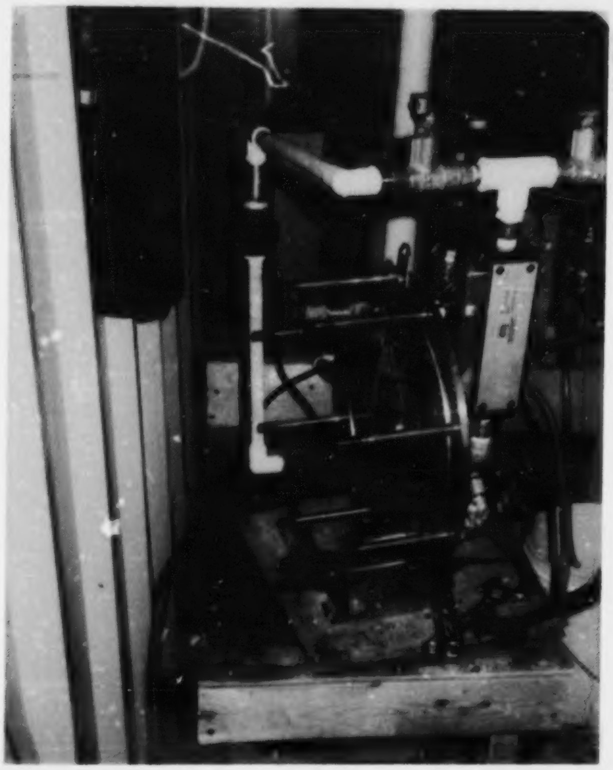

Figure 49. Sealing the septum manifold prior to operation.

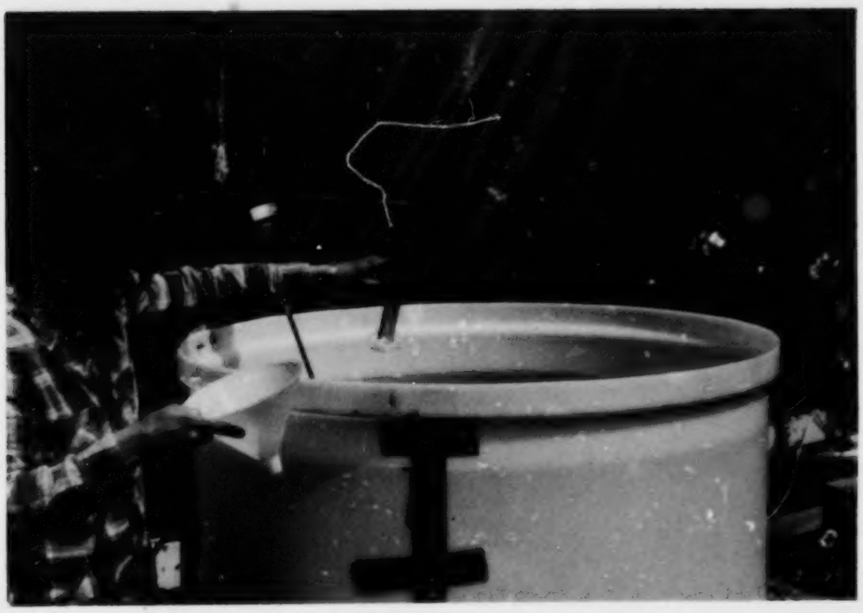

Figure 50. Adding Giardia cyst concentrate to the raw water feed tank.

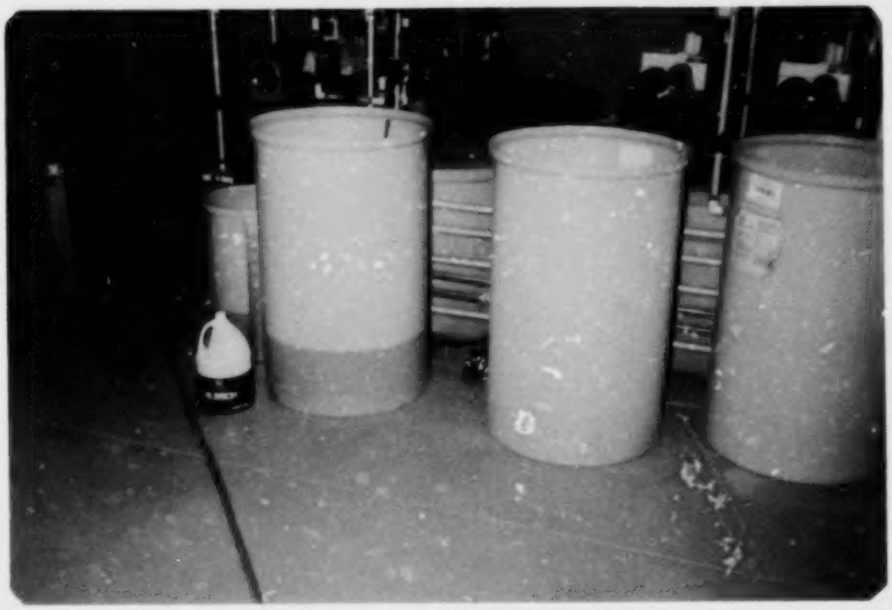

Figure 51. Four tanks used to hold effluent and backwash water from pilot plant for chlorination.

Figure 52. Bottled samples brought to test sites.

Figure 53. Samples and washwater refrigeration procedures at Fort Collins test site.

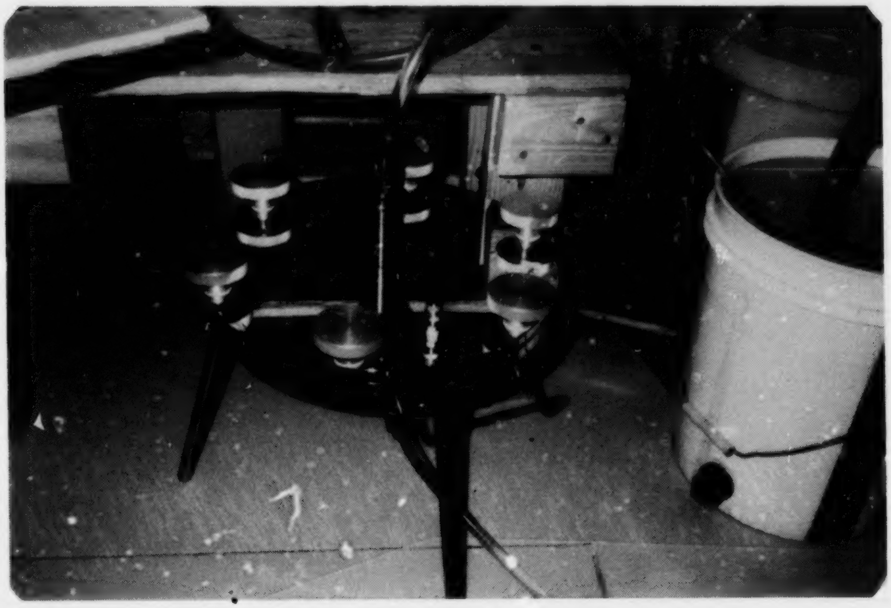

Figure 54. Stainless steel membrane filter holder used during field testing to collect Giardia cysts.

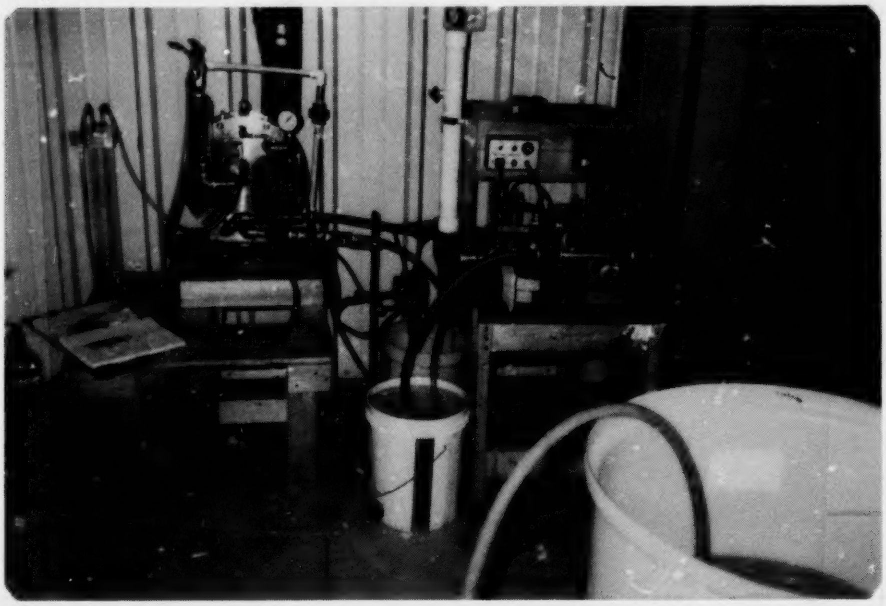

Figure 55. The pilot plant set up at Dillon Water Treatment Plant.

The membrane filter was used to sample the effluent stream one hour or until the pressure gauges on the pilot plant shown in Figure 55 registered a 10 psi increase.

At this time the filter was removed from the effluent stream, the excess water was removed from the filter housing by using an aspirator conencted to a garder hose, and the unit was disassembled and cleaned as shown in Figure 56.

While testing at the Fort Collins Water Treatment Plant, outdoor environmental conditions were also a concern. The precoat bucket had to be covered at all times to prevent wind-blown debris from clogging the precoat system shown in Figure 57. When the pilot plant was shut down after use, all of the pipelines and pumps had to be emptied to avoid freezing problems. The pilot plant was covered as shown in Figure 58 when not in use to provide more protection against environmental conditions such as wind, snow, and rain.

Testing Strategy

Grade size of diatomaceous earth was determined in the laboratory testing, described in Section 4, not to affect Giardia cyst removal. Therefore, the largest grade of diatomaceous earth used during laboratory testing, C-545, was used during all field testing. Extreme operating conditions were then imposed while using this grade to detemine if Giardia cysts could be removed under a wide range of conditions.

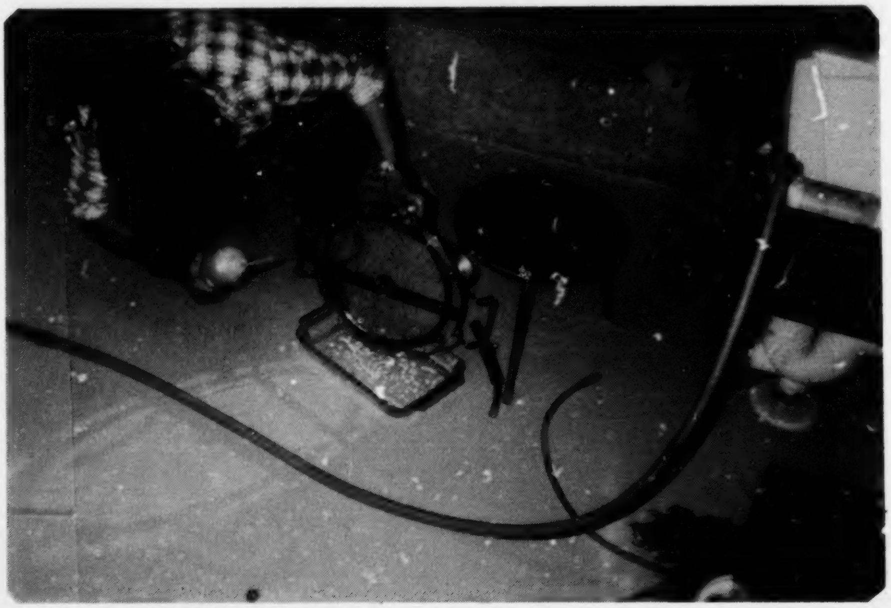

Figure 56. Washing the disassembled membrane sampling filter and filter holder.

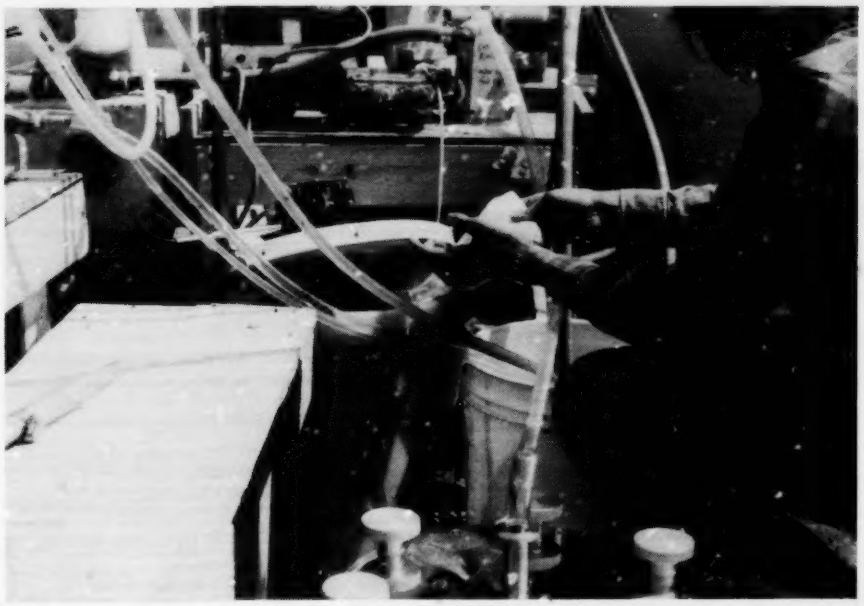

Figure 57. Adding diatomaceous earth to the covered precoat slurry bucket.

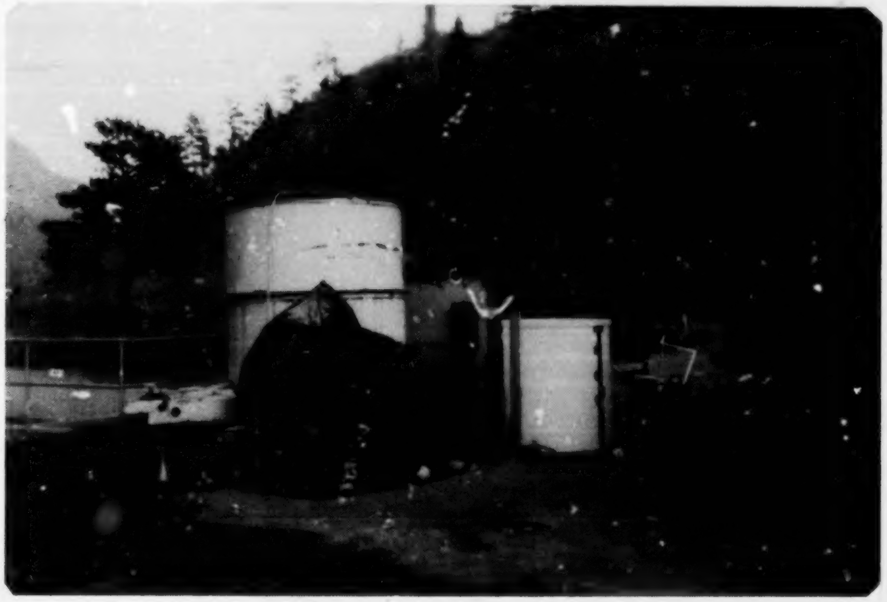

Figure 58. The diatomaceous earth pilot plant covered while not in use along side the trailer-mounted water boy rapid sand field testing unit.

The conditions of interest included hydraulic loading rate, temperature, influent *Giardia* cyst concentration, and turbidity. Hydraulic loading rates were 2.44, 4.88, and 9.76 m/hr (1.0, 2.0, and 4.0 gpm/ft^2). Temperatures were 3.5, 9, and 10°C. Influent *Giardia* cyst concentration ranged from 500 to 7,400 cysts/liter, added to the feed water. And influent turbidities ranged from 0.55 to 32.0 NTU.

Analysis of samples

All bacteria analyses were performed at nearby laboratories. While testing water from the Cache La Poudre River at the Fort Collins Water Treatment Plant the samples were collected, stored on ice, and brought back to the Engineering Research Center for analysis. At the Dillon Water Treatment Plant the samples were collected, stored in a refrigerator, and then taken to the Silverthorne Joint Sewer Authority for analyses. After samples were set up, the membrane filter plates and the standard plate count plates were brought back to the Dillon Water Treatment Plant and incubated in a portable dry air incubator brought from Colorado State University. At the Dillon site all microbiological supplies needed for the analyses, with the exception of a vacuum pump assembly and an autoclave, were brought from the Engineering Research Center.

Results

Table E-2 given in Appendix E, shows the raw data obtained from the field testing phase of diatomaceous earth filtration experiments. The findings of the field testing phase and its comparison to laboratory results follows.

Removal of Giardia cysts

A total of six test runs were conducted in the field. Two were at the Fort Collins Water Treatment Plant and four were at the Dillon Water Treatment Plant. The results from these tests are summarized in Table E-1. Table 30, extracted from Table E-1, shows the results of the *Giardia* cyst testing along with data on test conditions.

Results from Test Run F2, conducted at the Cache La Poudre River field test site are deemed invalid. Quality control procedures proved that a leak existed for this test run in the plumbing system of the diatomaceous earth filtration pilot plant. Testing with the 32 NTU turbidity water caused the pressure across the sampling membrane filter to exceed 30 psi in less than 5 minutes of filtering the pilot plant effluent stream, as it collected debris which passed through the filter cake onto the 5 μm pore size polycarbonate filter. It is believed that the O-rings on the central manifold of the filter septum plumbing may leak at pressures of 30 psi or greater. The pressure ~~relief valve on the~~ pilot plant was set at 30 psi but did not function properly during this test run.

Table 30 demonstrates again, but under field conditions, that diatomaceous earth filtration is an effective barrier to passage of *Giardia* cysts. Zero cysts were found in the effluent samples from the five valid test runs (i.e., those without leaks) conducted with Giardia cysts added to the influent source. Even the two most extreme test runs, one at a hydraulic loading rate of 9.76 m/hr (4 gpm/ft^2) and one at an influent Giardia cyst concentration of 7,400 cysts/liter, did not cause a Giardia cyst "breakthrough". The Giardia cyst removals, based upon detected cysts, were 100 percent for these five test runs. Table 30 also provides the estimated percent removals based upon "detection limit" calculation.

These data clearly supports the laboratory data, showing that zero cysts will be found in the effluent stream under a wide range of testing conditions and that Giardia cyst removals will be greater than 99 percent under all operating conditions imposed.

Removal of total coliform, standard plate count bacteria, and turbidity

The average influent and effluent concentrations and the average removal percentages of total coliform bacteria, standard plate count bacteria, and turbidity for the seven field test runs are shown in Table 31, constructed from data in Table E-2. The average removal percentages were calculated from measurements of concentrations in the flows to and from the filter, respectively. The results given are averages from all sampling during a given test run.

During field testing the main focus of experimentation was on the removal of Giardia cysts by the diatomaceous earth filtration process. But in addition, total coliform bacteria, standard plate count bacteria, and turbidity data were collected to evaluate the filtration process under ambient water conditions. Comparing the removal percentages in Table 31 with the average removals from laboratory testing, Table 10, it appears that the removals of total coliform bacteria, standard plate count bacteria, and turbidity determined from field data are higher.

Total coliform bacteria. Table 31 constructed from Table E-2 shows that the percent removal of total coliform bacteria for these test runs ranged from 42.0 to 97.0 percent. The three lowest percent removals occurred during: (1) test runs at higher hydraulic loading rates of 4.88 and 9.76 m/hr (2.0 and 4.0 gpm/ft^2); and (2) a test run which was conducted for 300 minutes of run time. These results show higher percent removals but generally are consistent with those obtained during laboratory testing using C-545.

Standard plate count bacteria. Table 31 shows that the average removal of standard plate count bacteria ranged from 18 to 84 percent for the seven diatomaceous earth filtration field test runs. Again, the lower removal percentages occurred at the test runs conducted at higher hydraulic loading rates of 4.88 and 9.76 m/hr (2.0 and 4.0 gpm/ft^2) respectively, and for a test run of 300-minute duration. The average influent concentration of standard plate count bacteria ranged from 408 to 35,000 colonies per milliliter for the seven field test runs.

Turbidity. Table 31 shows that the average removal of turbidity ranged from 21 to 77 percent for the seven field test runs conducted with

Table 30. Giardia cyst counts for diatomaceous earth filtration field tests. All Giardia cyst analysis of samples by micropipette techniques.

IDENTIFICATION		CONDITIONS							RESULTS				
						Influent Giardia[1] Cyst Concentration							
Date	Run No.	Grade	Filt. Rate (m/hr)	Temp. (°C)	Duration of Test (min)	Added to Feed Water (cysts/L)	Detected in Feed Water (cysts/L)	Effluent Volume Sampled (L)	Number of Cysts Detected in Analysis of Effluent Sample (No.)	Membrane Filter Sampling Efficiency[2] (%)	Cyst Detection Limit[3] (cysts/L)	Effluent Giardia[4] Concentration Corrected for Sampling Efficiency (cysts/L)	Giardia Cyst Percent Removal[5] (%)
4/17/83	F1	C-545	2.44	10	145	3950	--[6]	378	0	32.5	0.162	<0.162	>99.996
4/23/83	F2[7]												
5/5/83	F3	C-545	2.44	3.5	105	1000	229	227	0	22.9	0.385	<0.385	>99.962
5/6/83	F4	C-545	9.76	3.5	75	500	312	170	0	54.4	0.216	<0.216	>99.931
5/6/83	F5	C-545	4.88	3.5	90	1000	740	248	0	74.0	0.109	<0.109	>99.989
5/6/83	F6	C-545	2.44	3.5	65	7400	2278	132	0	30.8	0.492	<0.492	>99.993

[1] The "added" influent concentration, is the number of cysts contained in the feed tank as determined by analyzing the cyst concentration in a concentrated suspension of feces and adding this concentrate to a known volume of water in the feed tank. The "detected" influent concentration is obtained by sampling and analysis of the influent water from the feed tank.

[2] Membrane filter sampling efficiency = 100(Influent cyst concentration detected in feed water)/(Influent cyst conentration added to feed water).

[3] Cyst detection limit = (20 cysts/number of micropipette aliquots)/[(Membrane filter sampling efficiency)(Effluent volume sampled)]. The "20 cysts" is a multiplication factor inherent in the micropipette analysis technique.

[4] Effluent Giardia cyst concentration corrected for sampling efficiency = (No. of cysts detected in effluent)/[(Membrane filter sampling efficiency)/(Effluent volume sampled)]. If zero cysts were detected this value is taken as the detection limit.

[5] Giardia cyst percent removal = 100(Influent cyst concentration added to feed water - Effluent Giardia cyst concentration corrected for sampling efficiency)/(Influent cyst concentration added to feed water).

[6] The influent cyst concentration was not determined after the cysts were added to the storage tank. The sampling efficiency for these tests is taken as the average of all similar tests.

[7] A leak analysis was detected after this test and as a consequence the Giardia data has not been included.
NOTE: All Giardia cyst analyses were conducted by the micropipette technique.

Table 31. Average removals of bacteria and turbidity for seven diatomaceous earth filtration field test runs using grade C-545.

IDENTIFICATION		TEST CONDITIONS				MEASUREMENTS								
						Total Coliform			Standard Plate Count			Turbidity		
Date	Run Number	Temperature (°C)	Hydraulic Loading Rate (m/hr)	Duration of Test Run (min)	Rate of Pressure Increase (cm Hg/hr)	Influent (No/100 mL)	Effluent (No/100 mL)	Percent Removal (%)	Influent (No/1 mL)	Effluent (No/1 mL)	Percent Removal (%)	Influent NTU	Effluent NTU	Percent Removal (%)
4/17/83	F1 Poudre	9	2.44	145	0.00	100	3	97.0	35,000	5750	83.6	3.7	0.99	73.2
4/23/83	F2[1/] Poudre													
5/5/83	F3 Dillon	3.5	2.44	105	2.40	ND	ND	-	ND	ND	-	0.66	0.42	36.4
5/6/83	F6 Dillon	3.5	2.44	65	3.77	3500	1000	71.4	6000	1025	82.9	2.4	1.46	39.2
5/7/83	F7 Dillon	3.5	2.44	300	0.27	1875	891	51.1	408	141	65.4	0.86	0.68	20.9
5/6/83	F5 Dillon	3.5	4.88	90	2.20	2500	1450	42.0	1075	800	25.6	0.55	0.43	21.8
5/6/83	F4 Dillon	3.5	9.76	75	13.33	3500	1500	57.1	1100	900	18.2	0.58	0.34	41.4

[1/] Data in Run F2 was disregarded since a leak in the filter was detected subsequent to the test.

diatomaceous earth grade C-545. The highest removal percentage for any laboratory-conducted test run using grade C-545 was 24 percent. The average turbidity removal calculated from all laboratory tests using grade C-545 was only 13 percent when filtering Horsetooth Reservoir water characterized by fine particulates, called "glacial flour" for the purposes of this study.

The influent turbidity values ranged from 0.55 to 3.7 NTU for the six test runs conducted in the field. The 1 NTU standard was met for all test runs.

Conclusions

When evaluating these results it must be taken into consideration that influent concentration values varied considerably and that various water sources were used in the field. This qualification notwithstanding, field testing results generally confirmed the effectiveness of the diatomaceous earth filtration process as found in laboratory testing on the removal of Giardia cysts, total coliform bacteria, standard plate count bacteria, and turbidity. The removal percentages of these variables were considerably higher, however, than those determined in the laboratory phase of this research.

Because the effectiveness of the diatomaceous earth filtration process depends upon field site water conditions, it is recommended that pilot plant testing be conducted prior to the design and installation of any filtration system. This is, of course, recommended for any filtration process.

SECTION 7

DISCUSSION OF RESULTS

In this chapter the foregoing results are examined with respect to application in practice. The first section deals with removal effectiveness of diatomaceous earth as a process. The second addresses the role of operating conditions.

Removal Effectiveness of the Diatomaceous Earth Filtration Process

Of special interest is the effectiveness of the diatomaceous earth filtration process on removal of *Giardia* cysts. At the same time removals of bacteria and turbidity are of interest. Though it is not necessary to meet coliform standards by filtration alone, the process is required to provide a suitable water for disinfection. This is accomplished by the reduction, to a suitable level, of bacteria and other substances which exert a demand on disinfectants. Particle counts are of recent interest to researchers and operators. Whether this parameter can be an effective surrogate for other water quality indicators, such as *Giardia* cyst concentration, has practical interest, since the organism is so difficult to detect and measure.

Removal of Giardia cysts

Table 13 shows that diatomaceous earth filtration will effectively remove *Giardia* cysts from Horsetooth Reservoir water spiked with known cyst concentrations. *Giardia* cyst removals exceeded 99 percent for all of the diatomaceous earth grades tested, e.g., C-545, C-535, C-503, and Hyflo Super-Cel and for all conditions imposed. Cysts were found in the filtration effluent for only one test run (in which the cyst concentration was 33,600 cysts/liter).

Grade was not a limiting factor for *Giardia* cyst removal even though C-545 and C-535 have median pore sizes of 17.0 and 13.0 μm respectively. Conceivably, *Giardia* cysts which are ovoid to ellipsoid in shape with dimensions of 8 to 12 μm by 7 to 10 μm could pass through a filter cake of C-545 or C-535. They did not, however, when influent concentrations were below 10,000 cysts/L.

Probably, *Giardia* cysts are removed by straining as the raw water passes through the diatomaceous earth filter cake. It is doubtful that an attachment mechanism accounts for any measurable cyst removal. This is supported by DeWalle (1983), who found that the zeta potential of formalin-fixed *Giardia lamblia* cysts was -25mV at pH 5.5, and increases in electronegativity as the pH rises. Also, Oulman and Baumann (1964), showed that diatomaceous earth has an electronegative surface charge. Therefore, diatomaceous earth should not attract and attach *Giardia* cysts, and the removal mechanism must be straining.

The only limiting factor for complete *Giardia* cyst removal (zero cysts "detected" in effluent samples) was a high influent cyst loading. *Giardia* cyst breakthrough occurred only once, at a cyst loading of 33,600 cysts/liter. An influent concentration of 10,000 cysts/liter did not produce breakthrough. And it is doubtful that *Giardia* cyst concentrations this high would ever be found in any natural surface waters. The highest ambient cyst concentration found by anyone has been 0.08 cysts/liter, using 1 µm pore size fiber wound cartridge filters, Blair (1980). Even if the sampling and analysis efficiency was only one percent, this concentration would convert to only 8 cysts/liter.

A surrogate for *Giardia* cyst analyses was sought during the research. But since cyst breakthrough occurred for only one test a surrogate could not be determined. Particle analyses, however, could serve as a surrogate. The measurement provides information on removal of particles in the *Giardia* cyst size range, i.e. 6.35 to 12.70 µm, as well as other size ranges. Table 12 shows that particle count reductions in the 6.35 to 12.70 µm range are high, e.g. 94 percent median for all tests. If effluent particle counts in this size range are appreciably higher than what is expected for a given water, there is a cause for concern. The passage of excessive particles could indicate a malfunction in treatment and consequently a possibility for passing cysts. As an example, if C-545 grade is used the median particle size is 26 µm and the D_{10} particle size is 12.8 µm and so the majority of particles observed in the effluent in the 6.35 to 12.70 µm size range must be foreign.

Bacteria Removals

Table 10 shows that removals of total coliform bacteria and standard plate count bacteria followed similar trends even though removals of standard plate count bacteria were generally lower. The removals of bacteria are affected by all of the operating conditions, including: diatomaceous earth grade, hydraulic loading rate, influent bacteria concentration, run time, and alum coating. The effect of temperature was not clear, since influent bacteria concentration, which affected the percent removals, varied during temperature test runs.

The effect of diatomaceous earth grade on percent bacteria removal (and percent turbidity removal) is shown in Figure 59 which was derived from Table 15. It is clear that the use of finer grades of diatomaceous earth results in higher percent removals of bacteria. Bacteria removals for the water treatment grades range from 27 to 83 percent, the removals for the finer grades exceed 95 percent. While Figure 59 shows clearly that percent removals are strongly affected by diatomaceous earth mean particle size, which is a general conclusion, the specific relationship will be unique for the water being treated. For this reason, pilot plant testing is imperative for the water to be treated.

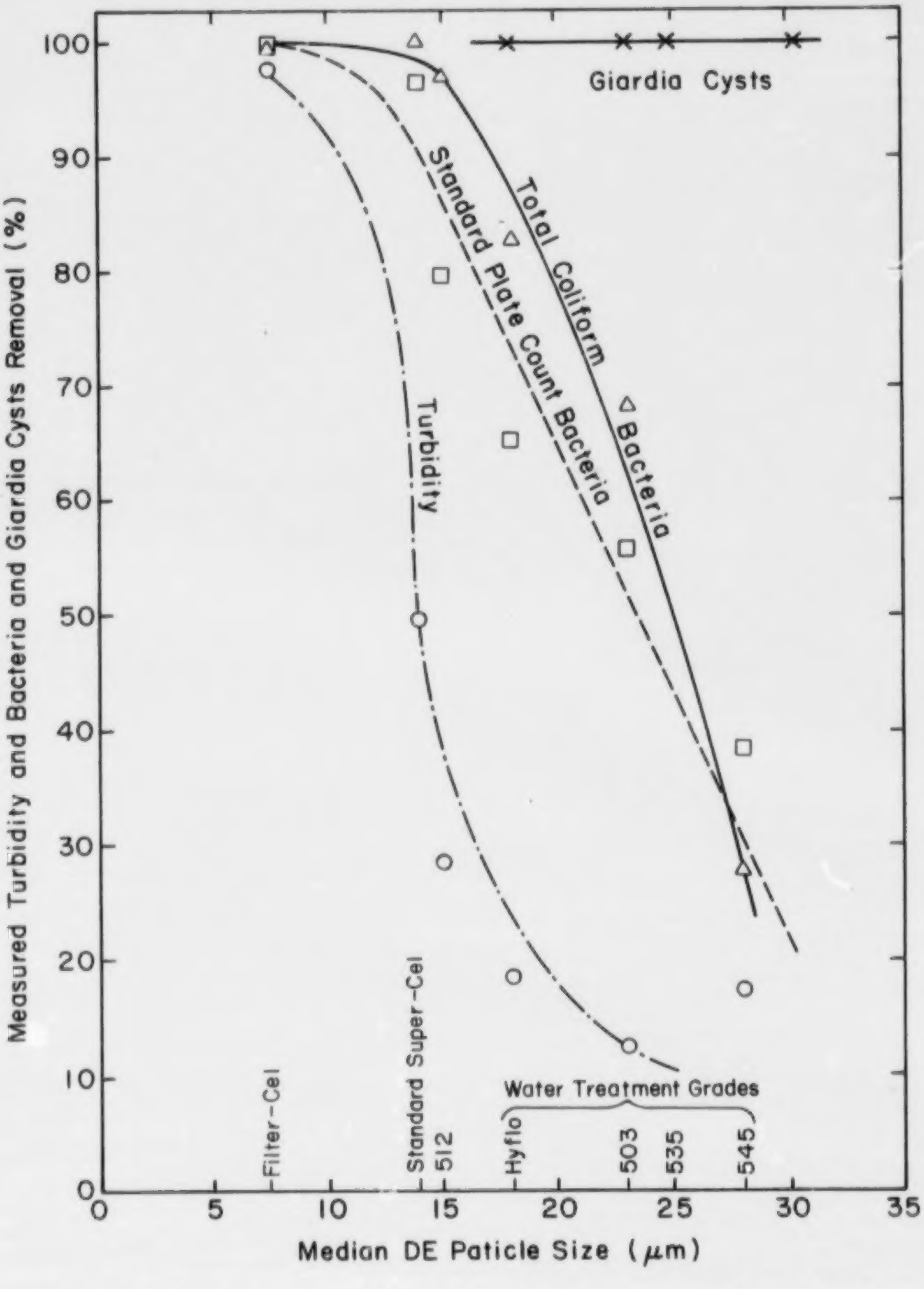

Figure 59. Bacteria removal as affected by diatomaceous earth particle size for test runs of five hour durations. Filtration rate was 2.44 m/hr. Plotted points obtained from Table 15.

Turbidity and particle removals

Figure 59 shows the effect of diatomaceous earth grade on turbidity removal. For the Horsetooth Reservoir water, having a "glacial flour" type of turbidity, the percent reductions were not below 1 NTU except for the finest grade of diatomaceous earth, i.e., Filter-Cel. Table 11 shows that the reason for these low removals is due to the size of the particles making up the turbidity, i.e. 27 percent of the turbidity will pass a 0.45 μm membrane filter.

Table 12 shows that particle removals, for 6.35 to 12.70 μm size particles, are uniformly high, e.g. 82 to 99 percent for even the C-545 grade of diatomaceous earth. Turbidity removal, however, is less than 20 percent for the C-545 grade. This result is expected since the majority of the turbidity particle sizes have been shown to be below the lower limit of particle size measured, i.e. 2.52 to 3.17 μm.

The effect of influent turbidity levels on percent reduction of turbidity is seen in Table 23, which shows that for the water treatment grades of diatomaceous earth higher influent turbidities are associated with lower removals of turbidity. Data are not adequate to show any trends for the finer grades.

Role of Operating Conditions

The role of operating conditions on process performance is reviewed here. Included are grade of diatomaceous earth, hydraulic loading rate, influent concentration, run time, temperature, and alum coating.

Grade of diatomaceous earth

The grade of diatomaceous earth had no effect on *Giardia* cyst removal, and not a great effect on particle count removals, for particles in the 6.35 to 12.70 μm size range. But, as seen in Figure 59, the effect of grade on removal of turbidity, total coliform bacteria, and standard plate count bacteria is marked. The grade of diatomaceous earth also affects the rate of pressure increase as is seen in Table 1 and Table 16.

Figure 59 also provides some information on expected bacterial removal for different grades of diatomaceous earth. Similar trends appear in the curves for total coliform bacteria and standard plate count bacteria removal. Probably because of the differences in the size distributions of the two groups of bacteria, their slopes and general shapes are different. Coliforms are relatively constant in size and removal appears to rise sharply from the largest particle size of diatomaceous earth. The standard plate count comprises a variety of sizes of bacteria; therefore, this curve should rise more gradually, which it does, showing removal of successively smaller bacteria. The shape of these bacteria removal curves should remain about the same for any water source. Turbidity removal versus diatomaceous earth particle size also increases with decreasing grade, but the shape of this curve, as seen in Figure 59, will be dependent on the characteristics of the raw water source.

Figure 60 shows percent removals of total coliform bacteria, standard plate count bacteria, and turbidity for different grades of diatomaceous earth. The data from the different test runs are plotted to show both the spread of the plotted points as well as their groups. Again, the effect of grade is clear from the trends in the groups of the three parameters shown.

Hydraulic loading rate

Figure 61 shows the effect of hydraulic loading rate on percent removals of particles, standard plate count bacteria, total coliform bacteria, and turbidity. The effect of hydraulic loading rate is unmistakable, but its effect is "nominal". Whether 2.44, 4.88, or 9.76 m/hr hydraulic loading rate is used in a design should depend upon factors other than removal effectiveness. For example, how it will affect rate of headloss increase and length of run would be a more important consideration.

Influent concentration of total coliform bacteria, standard plate count bacteria, and turbidity

Figure 62 shows the effect of influent concentration of total coliform bacteria on the percent removal of total coliform bacteria for four grades of diatomaceous earth. As the influent concentration increases the removal percentage decreases. The trend is similar for each of the four grades. The data shown for the C-512 grade show two points from our data (shown as squares) along with data from Hunter et al. (1966). They are compatible, thus providing independent support.

A similar relationship appears to exist for standard plate count, which is seen in Table 21. These results support the contention that removal percentages decrease with increasing influent concentrations. Our data do not show such a relationship for turbidity, however, since the spread in turbidity is quite narrow for Horsetooth Reservoir water.

Headloss

Headloss and rate of pressure increase in the filter vessel showed no effect on the removal of *Giardia* cysts, total coliform bacteria, standard plate count bacteria, and turbidity. A relationship does exist, however, between rate of pressure increase and effluent particle counts as was seen in Table 24. The number of effluent particles in the smaller size ranges were noticeably increased when the rate of pressure increase was high. As noted, this was believed to be due to filter cake attrition, which is affected by the rate of headloss increase.

Normal water treatment grades of diatomaceous earth will not exceed expected headloss requirements in a typical cycle length (sixteen to twenty-four hours) if the precoat addition is applied properly and a constant concentration of bodyfeed is supplied to the diatomaceous earth filter. Large rates of pressure increase did occur during several test runs when liquid dog feces were added to the raw water source; this however is not typical of a natural water. Pilot testing is required to determine what the headloss rate will be for a given water.

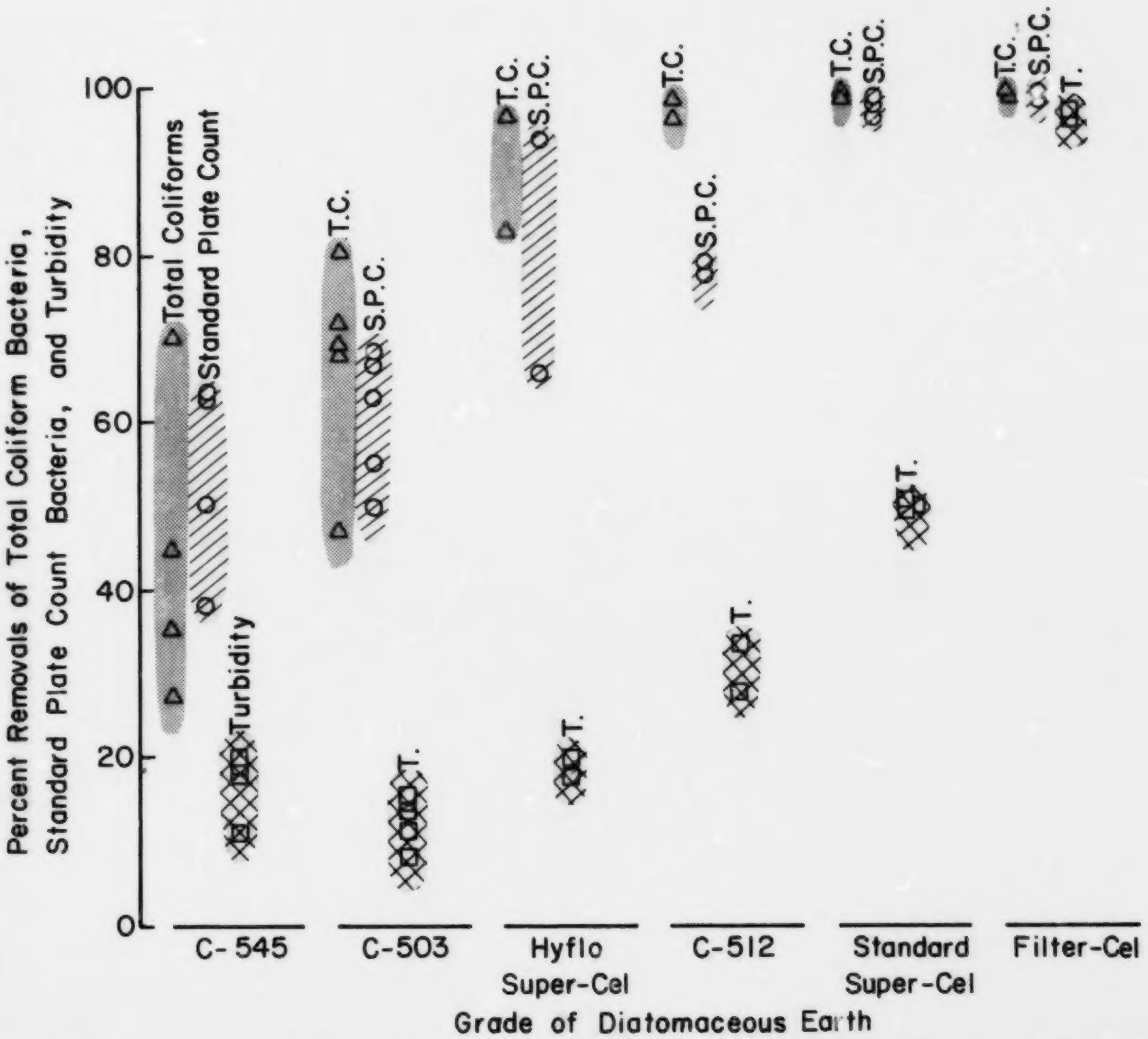

Figure 60. Percent removal of total coliform bacteria, standard plate count bacteria and turbidity for six grades of diatomaceous earth.

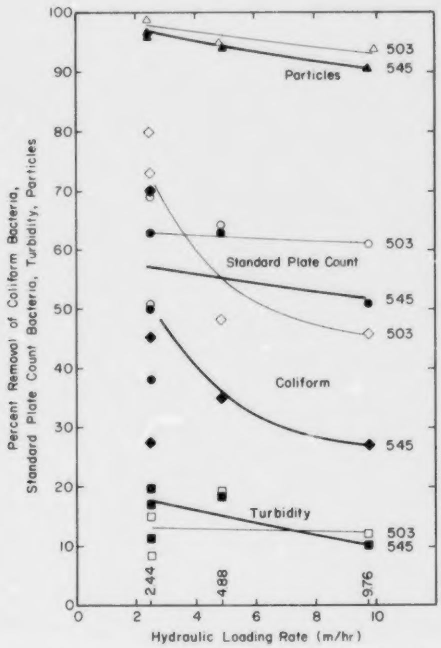

Figure 61. Hydraulic loading rate versus removal of particles, standard plate count bacteria, coliform bacteria and turbidity for diatomaceous earth grades C-545 and C-503.

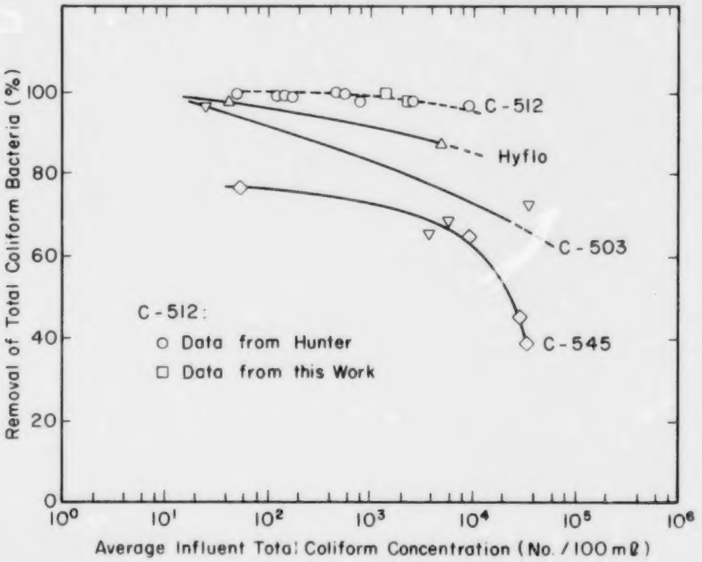

Figure 62. Total coliform bacteria removal as affected by influent concentration of total coliform bacteria for diatomaceous earth grades C-545, C-503, Hyflo, and C-512.

Run time

Figure 63 shows the effect of run time on percent removal of coliform bacteria. The percent removal declines with run time for six of the seven test runs plotted. This time dependent relationship probably is caused by the filtration mechanism of straining accompanied either by adsorption or by successive entrapment and release of total coliform bacteria. If total coliform removal was a function of straining only then the removal with time would be approximately a constant value or would increase with time as the number of large pores capable of passing coliforms decreased. Diatomaceous earth has a high liquid adsorption capacity but no research to date indicates that it has an adsorptive capacity for bacteria. Two "batch reactor" tests were conducted to determine if diatomaceous earth adsorbed bacteria. Both tests failed to show that bacteria adsorption occurred. Therefore, the trend in Figure 62 may be explained by the conjecture that bacteria are entrapped and then released as they work through the filter cake.

The data for standard plate count bacteria indicate that a similar relationship exists with run time. The data in Table E-1 indicate that as run time increases the removal of standard plate count bacteria decreases. The impingement and release of bacteria with increasing run time in the diatomaceous earth filtrate should not pose a problem as far as meeting water quality standards. The increased number of bacteria still would be controllable by normal post chlorination.

As discussed, removals of Giardia cysts were at 100 percent, even after 16 hours of testing. This is important to note as it is reasonable to question whether longer run time will result in cyst breakthrough. Turbidity removal also, seems not to be affected by run time.

Temperature

Temperature has no determined influence on the removal of *Giardia* cysts, total coliform bacteria, and standard plate count bacteria. A relationship could exist, but it is not clear from our data in Table 26 because of the possible countering of concentration. But Table 26 clearly shows that for turbidity, percent removals were significantly less, e.g. from 13 percent to 5 percent, when comparing 13°C with 5°C.

Alum coated diatomaceous earth

It is clear from Table 27 and Table 28 that alum coating of precoat and bodyfeed will increase markedly the effectiveness of the water treatment grades of diatomaceous earth in removal of bacteria and fine turbidity. These tables show that coliform bacteria removals when using alum coated C-503 and C-545 exceed 96 percent in all cases, while removal of coliforms without alum coating only averaged 58 percent for the same grades. Standard plate count bacteria reductions, for alum coating tests, exceeded 79 percent in one case and 93 percent generally; reductions without alum coating averaged only 63 percent. From this it is clear that alum coating will increase bacteria removal significantly, and may be warranted when reduced disinfectant demand is required.

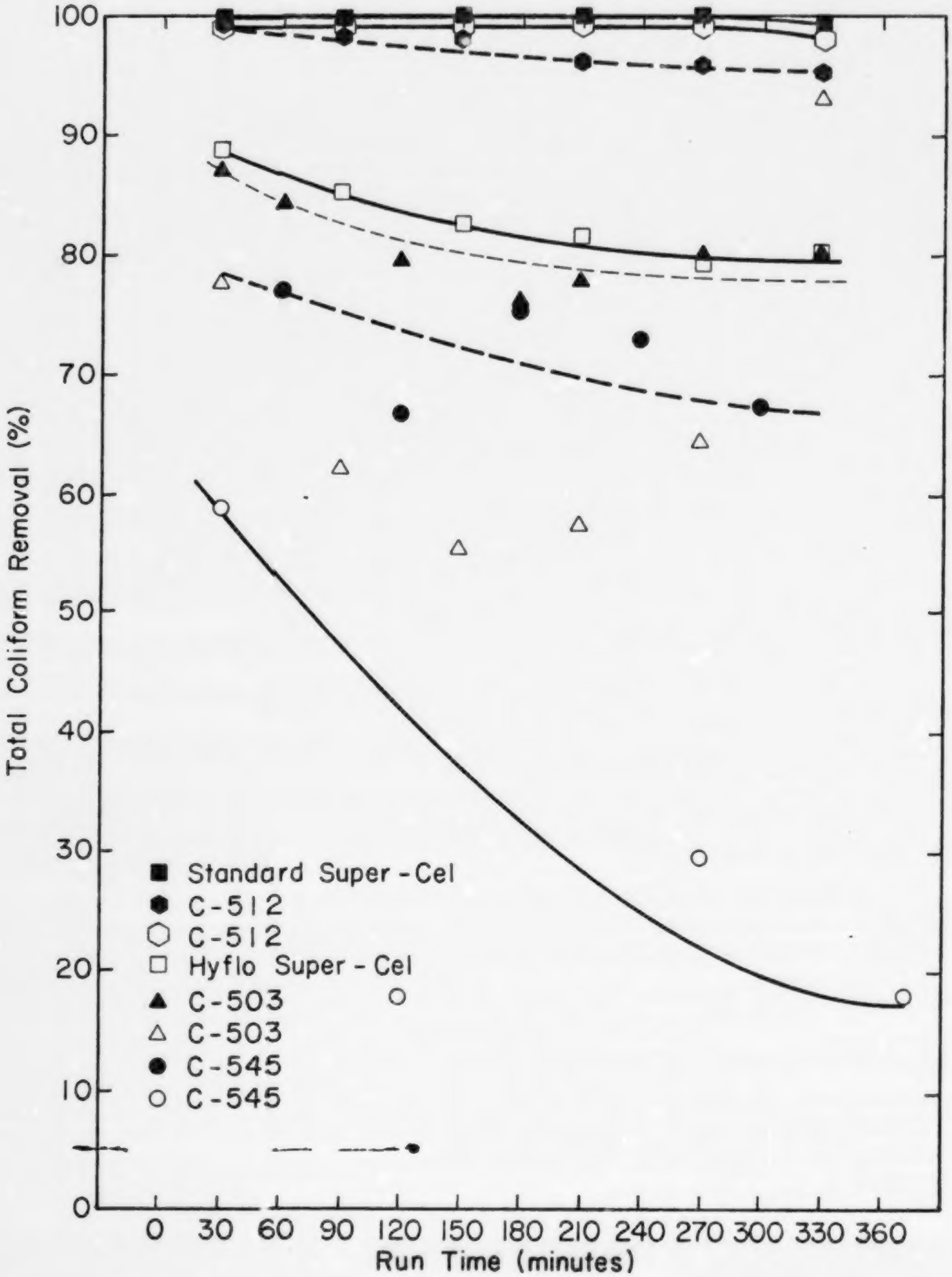

Figure 63. Total coliform bacteria removal as affected by run time for various diatomaceous earth grades.

Table 32 abstracted from Table 27 shows the relationships between alum concentration and 1) average turbidity removal and 2) average rate of pressure increase for C-503 and C-545. As the alum concentration increases, the average turbidity removal increases and the "average rate of pressure increase" increases. This table indicates also, that the smaller diatomite particle sizes, e.g., Grade C-503, having higher surface areas, requiring more alum before they perform as well as a larger grade. It is evident from these data that alum coating will increase the turbidity removal effectiveness of the water treatment grades of diatomaceous earth to acceptable levels, even for the "glacial flour" turbidity in Horsetooth Reservoir water. It is evident also that headloss will increase significantly when alum coating is used. Alum coating could be a valuable adjunct mode of treatment.

The use of alum to coat coarse grades of diatomaceous earth will improve the finished water quality but will require more expertise in operation of the filtration system. Also use of alum will shorten the length of the filtration cycle, significantly if alum concentrations are high.

Coating of the precoat diatomaceous earth with alum for application rates of 0.10 to 0.15 lbs/ft^2, instead of 0.20 lbs/ft^2 as was used in this investigation, could extend the length of the filtration cycle. If the bodyfeed addition is also alum coated, increased bodyfeed concentrations does not appear to extend the length of the filtration cycle. This appears to be caused by bridging and coagulation of particles, which is enhanced by the additional alum supplied to the filter cake. This will cause an increase in the rate of headloss increase.

Table 32. Average turbidity removal and average rate of pressure increase for various alum concentrations.

Grade	Run No.	Alum Concentration (%)	Turbidity Removal (%)	Average Rate of Pressure Increase (cm Hg/hr)
C-503	50	5[1]	79	6
	52	5[2]	94	13
	53	5[3]	99	19
	54	8	99	36
C-545	57	2	66	3
	48	4	86	7
	51	5	98	17

[1] Diatomaceous earth was coated 5 days prior to use.

[2] Diatomaceous earth was coated immediately prior to test run.

[3] Bodyfeed concentration was 50 mg/L instead of 25 mg/L.

GLOSSARY

Air Bump	A technique employing air used to clean the filter cake off the diatomaceous earth septum after the filtration cycle.
Attrition	Loss of material.
Blinding	The reducing or shutting of flow due to solid particles filling the openings in the filter media or septum.
Bodyfeed	The addition of diatomaceous earth during the filtration cycle to keep the filter cake porous.
Bridging	Joining of two or more particles by arching over individual openings in the filter septum or between the individual filter elements.
Cake	Solids deposited on the filter medium.
Calcined	The process used in manufacturing diatomaceous earth by melting and fusing particles.
Clarity	Clearness of a liquid as measured by a variety of methods.
Cycle	Filtration interval, length of time filter operates before cleaning.
Darcy	A unit measurement of permeability equal to the passage of one cubic centimeter of fluid of one centipose viscosity flowing in one second under a pressure of one atmosphere through a porous medium having a cross-sectional area of one square centimeter and one centimeter long.
Dependent Variable	Measurable variables such as total coliform bacteria and turbidity. The reduction in concentrations of these variables "depends" on the operating conditions employed.
Detection Limit	The minimum concentration of *Giardia* cysts that could be detected by the sampling and counting procedure used in measuring *Giardia* cysts.
Diatomaceous Earth	Siliceous, porous deposit made of opaline shells of diatoms, used as a filter-aid, paint filler, adsorbent, abrasive, and thermal insulator.

Diatomite	Consolidated diatomaceous earth. Rock compounded mainly of diatom residues.
Differential Pressure	The difference in pressure between two given points, usually across the filter cake, precoat, septum and filter leaf, usually expressed as ΔP.
Feed	The mixture of particles and fluid that is introduced into the filter. Terms used synonymously include influent, incoming slurry, and raw water.
Filter-Aid	Same as filter media in diatomaceous earth filtration, otherwise known as the various chemicals used in rapid sand filtration to enhance particulate removal.
Filter Cake	The layer of diatomaceous earth and particulates that build on the septum from precoat, bodyfeed, and filtration of suspended solids in the raw water.
Filter Medium	The permeable material that separates particles from a fluid passing through it.
Filter System	The combination of a filter and associated hardware required for the filtration process.
Filtrate	The fluid that has passed through the filter. Used synonymously with effluent. The discharge liquor in filtration.
Filtration	The process by which particles are separated from a fluid by passing the fluid through a permeable material.
Filtration Rate	See hydraulic loading rate.
Flow Rate	Also known as rate of flow. Time required for a given quantity of flowable material to flow a measured distance.
Flux	A substance added when calcining diatomaceous earth to enhance the melting and fusing of particles.
Flux Calcined	The process used in manufacturing diatomaceous earth by adding a flux (soda-ash) and melting and fusing particles.
Hydraulic Loading Rate	The total volume of liquid per unit time per square unit of filter area. Same as filtration rate.
Independent Variable	Operating conditions which effect the removal efficiency of dependent variables.
Media	Material of controlled pore size used to remove foreign particles from fluids.

Membrane	Media through which a liquid is passed; usually associated with a very fine or tight type of filtration.
Mesh	Number of openings in a lineal inch of wire cloth.
Micron	A metric unit of length; 10^{-6} meters.
Operating Conditions	Also known as independent variables and operating parameters. The various conditions under which the filtration process can be operated.
Operating Parameters	See operating conditions.
Particle Size Distribution	The distribution obtained from a particle count grouped by specific micron sizes.
Perlite	A media used in the precoat filtration process which is processed from volcanic ash. Also available in a variety of grades.
Permeability	The property of the filter medium that permits a fluid to pass through under the influence of differential pressure. The ability of a material to permit a substance to pass through it.
Porosity	Property of a solid which contains many minute channels or open spaces. The fraction as a percent of the total volume occupied by these channels or spaces.
Precoat	The diatomaceous earth addition added to form a layer of media on the septum before filtration begins.
Precoat Filtration	The generic name for the diatomaceous earth filtration process. Other media besides diatomaceous earth such as perlite can be used in this filtration process.
Precoating	The depositing of an inert material such as diatomaceous earth, onto the filter medium prior to the filtration of suspended solids from a solid-liquid slurry.
Recycle	The series of passing a precoat slurry from the precoat bucket through the filter until all the diatomaceous earth in the precoat has bridged on the filter.
Septum	A permeable material used to support the filter medium.
Testing Space	Range of testing.

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APPENDICES

APPENDIX A

OPERATING INSTRUCTIONS FOR ONE SQUARE FOOT PRESSURE LEAF FILTER[1]

A. Preliminary Setup

1. Close all valves in the system. There are 12 valves in all.
2. Make sure all hoses are connected. There should be a hose to carry influent to the influent valve, a hose from the precoat tank to the precoat inlet valve, a hose from the feed pump discharge to the filter inlet, a hose from the filter drain valve to drain, a hose from the filtrate valve to drain and a hose from the precoat recycle valve to the precoat tank. There should also be small diameter Tygon tubing from the bodyfeed tank valve to the bodyfeed inlet valve and a drain hose from the bodyfeed drain valve.
3. Set all switches on the filter unit to the off position. Set the pressure controller on the control box at 40 psi and place a new chart on the recorder. Turn on the master switch and the pump control switch.
4. Thread the Tygon tubing through the bodyfeed pump and turn the wing nuts all the way on the pressure plate. The size tubing is selected from Table 1 based on flow rate.
5. Fill the bodyfeed tank with 50 liters water (1 cm depth equals 1.13 liters) and fill the precoat tank to the black line (use drinking water or filtrate from a previous run).

B. Precoat

1. Weigh out filter aid to be used for precoat and bodyfeed. The amount of filter aid to be used for bodyfeed can be calculated based on the desired flow rate of the bodyfeed pump and the dosage in the influent. The precoat is usually 0.1 lbs (45 gm) per square foot. For extra protection, 0.15 lbs (68 g) or 0.20 lbs. (90 g) per square foot may be used.

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[1] Modified from Johns-Manville original to delete references to Figures.

2. Open the following valves (see Figure 1):
   - Precoat inlet valve
   - Filter inlet valve
   - Precoat recycle valve
   - Air vent

   Figure 3 shows the flow circuit for precoating. Be sure all other valves are closed.

3. Turn on the feed pump (marked "Aux. Pump").

4. When the filter shell is full, close the air vent. Set the flow (small wheel with handle on the speed reducer) at 1.5 to 2.0 gpm. NOTE: Whenever a flowmeter is used for the first time, it should be calibrated.

5. Add the precoat filter aid to the water recirculating in the precoat tank. Using a paddle or large spatula, agitate the slurry for about five minutes then only occasionally until the water in the shell is clear.

6. While waiting for the precoat to go on, add the filter aid for bodyfeed to the bodyfeed tank and start the mixer. Pull the tubing off the bodyfeed inlet valve and open the bodyfeed tank valve.

7. Start the bodyfeed pump. With the pump running turn the wing nuts on the pressure plate in until there is almost no motion to the nuts. Adjust the speed to the flow rate selected (using a graduated cylinder and stopwatch).

8. Turn the bodyfeed pump off and reconnect the tubing to the bodyfeed inlet valve.

   PLEASE NOTE: Once the precoat cycle has started, you cannot shut down the feed pump. If the pump should shut down during precoat or filtration cycles, the filter must go through the cleaning cycle and be reprecoated.

C. Filtration

1. Turn the speed adjuster on the feed pump down, slowly, adjusting the flow to desired flow rate (usually start at 1 gpm and change later if desired).

2. Open the bodyfeed inlet valve and start the bodyfeed pump. Run the bodyfeed for about 2-3 minutes.

3. The flow pattern for the filtration cycle is shown in Figure 3 filtering.

4. After the bodyfeed has run for 2-3 minutes (still on the precoat cycle), check to be sure that all valves are open on the influent line up to but not including the influent valve.

5. Open the influent valve and close the precoat inlet valve. NOTE: ALWAYS OPEN ONE VALVE BEFORE CLOSING THE OTHER VALVE.

6. Open the filtrate valve and close the precoat recycle valve. Trace the flow pattern.

7. The filter cycle will continue until a) the operator shuts down, or b) the pressure regulator shuts the system down at 40 psi. The pressure regulator is also designed to shut down the pumps if there is a power outage. In case of a power outage, the pumps must be restarted manually by pushing the red start button in the blue regulator box. PLEASE NOTE: As stated in the Precoat Section, if the pumps shut down for any reason, you must clean the filter and precoat again before going to the filtration step.

D. Cleaning

1. If the pumps have been shut down by the pressure regulator (at 40 psi), turn both pump switches to the off position then push the red start button. To shut down the system manually, simply shut off the two pumps.

2. Open the bodyfeed drain valve. Keep the stirrer on so that the filter aid will not settle to the bottom of the tank.

3. Open the filter drain valve and air vent (in that order).

4. Fill the precoat tank with clean water (drinking water or filtrate).

5. Open the precoat inlet valve, close the influent valve and the bodyfeed inlet valve.

6. Start the feed pump. The flow pattern for cleaning is shown in Figure 5. Turn the speed adjuster up 4 turns (there should be a fair amount of agitation on the bottom of the filter shell).

7. Open the spray cleaner valve and the spray cleaner gauge valve. Set the pressure regulator to 45 psi.

8. SLOWLY close the filter inlet valve until the spray cleaner gauge is about 40 psi. Rotate (clockwise) the filter using the handle on the backside of the shell until the spray has cut all of the filter cake off the screen.

9. Open the filter inlet valve and close the spray cleaner valve and gauge valve.

10. Be sure the supply of clean water is kept up in the precoat tank. Continue to flush the shell until all of the filter aid is washed out. This can be facilitated by closing the filter drain valve until the filter shell is half full and then opening the drain valve. This cycle repeated several times will usually flush out the filter aid from the shell. If it does not, shut off the pump, drain the shell, remove the wing nuts on the back plate of the shell and remove the plate and acrylic shell and clean. When reassembling the shell make sure the o-ring in the shell sits in the recessed groove in both the front and back plates. Tighten the wing nuts as tightly as possible by hand. Do not use tools to tighten the nuts as this could ruin the plastic shell.

11. Flush out the bodyfeed tank with clean water. Close the bodyfeed tank valve, remove the tubing from the bodyfeed inlet valve and turn the wing nuts on the pressure plate of the bodyfeed pump in until all four springs behind the plate are compressed.

12. Open the bodyfeed tank valve and flush the tubing with clean water.

13. Drain both tanks and the filter shell. The unit is now ready to run again.

APPENDIX B

TESTING THE DIATOMACEOUS EARTH FILTER FOR PLUMBING LEAKS

B.1 Testing for Plumbing Leaks

During the June 1982 visit of Dr. Baumann, a leak was discovered in the one square foot diatomaceous earth pilot filter. A "leak" is defined here as any opening between the two sides of the filter septum, other than the septum, which permits the passage of water being filtered. Prior to further experimentation it was necessary to determine if there was a leak in or around the filter septum. The following section describes the tests and analyses performed to determine whether leaks existed. These tests provided evidence that after modifications to correct the problem, no leaks existed. The tests showed that even with no leak diatomaceous earth still passes through the septum continuously. Apparently this is attrition of the precoat.

Two tests were performed to determine if a leak existed in the filter septum, the sealing, and the plumbing. Results are given in Tables B-1 and B-2, respectively. The tests were designed to verify those particles of appropriate sizes were removed by the filter. If the filter has no leak, particles should not be detected other than those passing through or breaking off the filter cake. Such a leak, if in the plumbing or filter septum seal, might be expected to pass larger particles than normally found in the filtrate. The tests were conducted by precoating the filter and then subjecting it to a sequence of influent waters as follows: (1) tap water, (2) tap water with a suspension of diatomaceous earth particles (bodyfeed amount), and (3) tap water.

Table B-1 shows results from the first test. The filter was precoated with Filter-Cel the smallest grade of diatomaceous earth tested, followed by the filtration of tap water, with diatomaceous earth added, and finally tap water. Columns A and B show the influent particle counts for tap water and tap water with diatomaceous earth added. Diatomaceous earth was added to increase the influent particle counts. Columns C, D and E are average effluent particle counts while the influent is being subject to the tap water + D.E.. Thirty minutes was allowed to elapse between samples to allow for flush out of the system. Flush out is 99.99 percent complete in 20 min at 1 gallon per minute according to the first order differential equation for a complete mixed system.

Comparison of columns C and D in Table B-1 would indicate that there might be a leak, since a large number of particles in the smaller size ranges are being discharged. When comparing columns D and E, however, it can be concluded that there is not a leak, since the particle counts are approximately the same. This discrepancy was investigated further and it was determined that there was not a leak and that the results are caused by precoat attrition. In either case, particles above 16.0 μm are not passing the septum since all particle counts in the size ranges above 16.0 μm are not statistically different than zero.

Attrition refers to the continual discharge of diatomaceous earth from the filter due to a "collapse" at the septum of the media in the precoat and its resulting release. This is a small quantity of diatomaceous earth but it does present problems when using a particle counter to evaluate the effluent since it is difficult to distinguish between those particles which might be passed through the filter and those caused by attrition. Attrition appears to be a function of the pressure increase in the filter; the greater the rate of pressure increase the greater the attrition.

Columns F and G in Table B-1 and, K and L in Table B-2 demonstrate the effect of pressure on attrition. In the first case (columns F and G) the differential pressure was raised by 25.85 cm Hg instantaneously, and after a sample was taken the pressure was returned to its original value. As can be seen a large number of particles in the smaller size ranges were discharged during the pressure increase and after the reduction the lowest counts observed were obtained. In the second case (columns K and L) the differential pressure was allowed to rise naturally while using tap water as the influent and then the pressure was raised instantaneously. Again an increase in particles was observed. These two tests demonstrate the marked effect pressure has on particle levels in the effluent of a diatomaceous earth filter.

Table B-2 shows results from the second test to determine whether a leak existed while taking attrition into account. Particle contaminated water was used as the initial influent, columns C, D, E, and F. Next, particle free water (filtered tap water) was used while trying to adjust the pressure to simulate the rate of pressure increase that occurred during the particle addition, columns G, H, I and J. The pressure was increased by increasing the flow slightly. As can be seen the pressure was increased slightly more than necessary but the results indicate as before that there probably is not a leak and that precoat attrition accounts for the effluent particle concentration.

Bacterial analyses were used as a final method to test for leaks. Table B-3 contains the influent and effluent coliform analyses observed while testing with various grades of diatomaceous earth. These test results agree with those presented by J. V. Hunter (JAWWA, 58:9, 1966) thus confirming the absence of leak in the diatomaceous earth pilot filter.

The absence of a leak in the filter mechanism was substantiated by the particle and bacterial analyses. It also became apparent that filter precoat attrition does occur and that the rate of pressure increase has a marked effect on the rate of attrition.

Table B-1. First test using particle counting to determine if leaks exist in the one square foot diatomaceous earth filter. Filter was precoated with JM Filter Cel.
(Number of Particles/10 ml)

Particle Size Range (μm)	Influent		Effluent Values for the Indicated Influent Water Conditions				
	Tap Water (A)	Tap Water + DE (B)	Tap Water (C)	Tap Water+DE (D)	Tap Water (E)	Tap Water and Increased Differential Pressure (F)	Tap Water and Decreased Differential Pressure (G)
2.52-3.17	5676	215056	877	2248	2311	6112	92
3.17-4.00	3140	184417	323	763	871	1896	44
4.00-5.04	2107	171327	149	352	417	741	36
5.04-6.36	1148	120393	68	149	175	294	12
6.36-8.0	521	66101	39	71	71	133	3
8.00-10.08	205	33164	23	39	27	65	0
10.08-12.7	63	15141	12	20	11	32	0
12.7-16.0	24	6027	7	9	5	13	1
16.0-20.2	3	2459	0	1	1	0	0
20.2-25.4	1	1025	1	1	3	1	0
25.4-32.0	1	443	1	3	1	1	0
32.0-40.3	0	172	0	0	0	0	0
40.3-50.8	0	56	0	0	0	0	0
Average Pressure (cm Hg)			69	79	87	115	89
Increase in Filter Differential Pressure over Time (cm Hg/min)			0.14	0.33	0.12	25.85	0

Table B-2. Second test using particle counting to determine if leaks exist in the one square foot diatomaceous earth filter.

Particle Size-Range (μm)	Filtered Tap Water	Tap Water + DE	Tap Water + DE Influent				Tap Water				Tap Water with Pressure Constant	Tap Water with Pressure Increase
	A	B	C	D	E	Average F	G	H	I	Average J	K	L
2.52-3.17	326	18840	325	258	162	248	2717	1268	607	1531	93	307
3.17-4.00	85	11810	98	98	69	88	880	552	189	540	52	131
4.00-5.04	38	12229	82	68	42	50	401	301	99	267	21	70
5.04-6.36	12	11656	38	33	13	28	158	132	47	112	4	22
6.36-8.00	4	9467	25	22	5	17	73	56	22	50	7	9
8.00-10.08	1	6967	12	12	3	9	25	30	12	22	3	0
10.08-12.7	4	4754	9	9	3	7	26	27	8	20	3	3
12.7-16.0	3	2719	9	3	0	4	13	16	5	11	1	0
16.0-20.2	0	1321	3	4	1	3	16	10	0	9	4	3
20.2-25.4	0	640	1	1	0	1	4	1	1	2	3	1
25.4-32.0	1	294	0	5	0	2	1	1	1	1	1	0
32.0-40.3	1	123	0	1	0	0	3	1	1	2	0	0
Time (after start up in min)			20	25	30		70	75	80		100	102
Pressure (cm hg)			13.5	13.5	13.6		15.5	15.8	16.0		16.2	22.5
Pressure increase (cm hg/min)			0.06	0.06	0.06		0.35	0.06	0.04		0.01	3.15

Note: 99.99 percent flush out of the filter occurs in approximately 20 min at 1 gpm.

Table B-3. Coliform bacteria concentrations at 0.5 and 1.5 hours for various grades of diatomaceous earth.

Grade of Diatomaceous Earth	Median Particle Size (μm)	Filtration Rate (gpm/ft^2)	Influent Coliform Concentration (#/100 mL)	Coliform Concentration at Stated Hour (#/100 mL)		Hunter, Bell, and Henderson's Coliform Concentration at Stated Hour[1] (#/100 mL)		
				0.5 hr	1.5 hr	Influent	0.5 hr	1.5 hr
Filter Cel	7.5	1	960	<1.0[2]	<1.0	ND[3]	ND	ND
Standard Super-Cel	14	1	6200	<1.0	<1.0	7000	0	0
C-512	15	1	3800	13	44	14000	34	43
Hyflo Super-Cel	18	1	4000	440	600	2270	50	20
C-503	23	1	6100	1700	2100	340	110	70
C-545	26	1	30000	15000	18000	1300	560	600

[1] Coliform concentrations for runs using 30 mg/L bodyfeed concentration as determined by J. V. Hunter et al., "Coliform Organism Removals by Diatomite Filtration," JAWWA, 58:9 (September, 1966), pp. 1160-1169.

[2] When value measured was zero a <1.0 is used.

[3] No data available for this grade.

APPENDIX C

PROCESSING DOG FECAL SAMPLES AND CYST COUNTING TECHNIQUES

1. Securing Giardia Cysts

Giardia cysts are obtained from fecal samples of infected dogs. Positive Giardia samples commonly appear as soft to watery stools but normal, firm stools should not be excluded as possibilities. Puppies about six weeks old are the best source but older dogs, bitches,and kennel dogs break frequently.

Fecal samples are collected in baggies and securely closed with twist-tie type closures. Samples are labeled with the pen number, dog number, etc. for future reference and notifying appropriate personnel of the results. The samples are placed in a cooler with ice and transported to the laboratory.

2. Preparing Cysts for Experimentation

In the laboratory, Zinc sulfate Flotations are performed on each fecal sample to check for the presence of Giardia cysts (procedure is described below). If cysts are present, the sample(s) are weighed and added to an equal amount of cool distilled water. The sample is then mixed thoroughly to break apart any aggregates.

If the sample appears extremely dirty it may be filtered through cheese cloth or gauze or the solution may be mixed thoroughly, quickly allowed to settle, poured into another container and the sediment discarded. Each of these procedures will, however, result in the loss of some cysts. Cyst samples and suspensions are refrigerated at all times.

3. Cyst Counting Techniques

There are two counting techniques used to quantify cyst in a sample, 1) Stoll dilution, and 2) micropipette. For a sample with a large number of cysts, i.e. a fecal suspension, the Stoll technique is usually used; the micropipette technique, however, also may be used. For a sample with a low cyst population, the micropipette technique is used. This is the technique used on all the samples collected during diatomaceous earth filtration experimentation. The zinc sulfate floatation technique is only used to identify cysts in a fecal sample.

3.1 Stoll Dilution Technique

Add 3 ml. Lugol's Iodine to a Stoll flask and fill the flask to the 56 ml. mark with cool distilled water. Mix the fecal suspension well and remove 4 ml. liquid. Add the 4 mls. to the flask and shake thoroughly. A 0.075 ml aliquot is removed via micropipette and is placed in a vaseline well. A coverslip is affixed and the number of cysts counted at 400x. The total number seen on one slip is multiplied by 200 to give the total number per ml sample. A minimum of 2 coverslips should be read and averaged.

3.2 Micropippette Technique for Samples from Experimentation

Samples will arrive at the laboratory and must sit overnight to allow settling of the cysts and debris. The following day the samples are pipetted down to approximately 200 ml. liquid without disturbing the sediment. After the excess water is removed, mix the sample well and pour in a 50 ml conical centrifuge tube. Centrifuge for 5 minutes at 1500 rpm. Pipette off the supernant to about 5 mls and repeat the procedure until all the sample has been concentrated to 1 ml and the sample jar rinsed well with distilled water. The final volume of the concentrate will depend on the amount of debris present in the sample.

To a 1 ml concentrate add 5 to 6 mls Lugol's Iodine and to a 5 ml add 10 to 15 mls Iodine. Mix the sample thoroughly and remove a 0.050 ml aliquot via micropipette. Place in a vaseline well, affix coverslip, and scan entire slipe at 400x. Note the characteristics of the debris present (protozoa, amorphous, fungal bodies, etc.) and count the number of cysts if any. If cysts are seen a minimum of two aliquots are counted and averaged.

To calculate the number of cysts present in the entire sample the number is multiplied by its corresponding dilution factor, i.e.

a 1 ml concentrate is multiplied by 20
a 5 ml concentrate is multiplied by 100
and a 10 ml concentrate is multiplied by 200

All results are recorded and reported on the standard forms as attached. Information which must be included is: date, information included on the sample label, initials of the analyst, counts of duplicate sample readings, final cyst number reported and the observations of the debris appearance.

3.3 Zinc Flotation for Cyst Identification

A fecal sample about the size of a pea is placed in a centrifuge tube, 5 to 6 drops of Lugol's Iodine is added and the sample is mixed well. Fill the tube half way with Zinc Sulfate solution (spgr 1.18 or 1.20) and mix well. Fill the tube with more solution until the meniscus bulges and affix a coverslip. Place the tube in the centrifuge and tap the coverslip with a pencil end to form a secure bond. *If the coverslip is not firmly in place it will come off during centrifugation and the procedure will have to be repeated. *The coverslip must always be handled by its edge as body oils will prevent attachment of the cysts to its surface. Centrifuge the samples at 1500 rpm for 5 minutes. Remove the coverslip and place on a glass slide. Examine the coverslip for Giardia at 100x magnification.

4. Labeling and Storing

Sample containers should be labelled with the date and the number of cysts per ml. The sample should be counted at least every 3rd day and/or before a portion isused to ensure accurate counts and cyst condition.

5. Reagents and Supplies

Lugol Iodine

1000ml warm distilled water
100gm Potassium Iodine
50gm Iodine
Mix till Iodine crystals are in solution. Store in dark bottle - light will deactivate the solution.

$ZnSO_4$ Solution

2-3 gallons distilled water
3 kg or 1-6.61b jar of $ZnSO_4$ crystals
Mix till crystals are in solution, place hydrometer into solution to read specific gravity. Keep adding $ZnSO_4$ till a specific gravity of 1.18 or 1.20 is reached. Store in one gallon glass jars.

Coverslips

VWR Micro cover glasses 1 ounce
    Cat No. 48366-227
    22 x 22mm No. 1½

Slides

Scientific Products Micro Slides
Plain Pre-cleaned
1.2mm thick Size 3 x 1 inch
Cat. No. M6130

Micro-pipette Tips

Micro-selectapette pipette tips
Siliconized - For - micro - pipetting
50-75-100ul 250 pipettes
Clay Adams Re-order No. 4711
Cat. No. 53517-423 VWR

6. *Giardia* Sources

CRHL - Collaborative Radiological Health Laboratory

Foothill Campus - Beagle Colony

Call Esther 491-8522 ext 29 for clothes in women locker
Jim Winic 491-8522 for information on puppy liters
(age, births, breeding, etc.)

Humane Society for Larimer County

6317 Kyle Av. Ft. Collins 226-3647
Collect at 7:30 am (before cage cleaning)
1:00 pm (after feeding)
Call before collecting to alert staff

Vet. Teaching Hospital

Parasitology Lab 491-7101 ext 233
Glenda Taton (Parasite Lab Tech) will collect
heavy infected samples

Oncology - Vet. Teaching Hospital

Oncology 491-7101
Call Dee or Sharon or Dr. Gillette
They use beagles from CRHL which break with Giardia
when moved to the Vet. Hospital

GIARDIA QUANTITATION

Filtration System ____________________

Run Information (sample label)	Analysis Date	Am't. Conc. in Sample	Analysis by	Counts of Replicates	Cyst # Reported	Observations and Comments

APPENDIX D

DETERMINATION OF CYST DETECTION LIMITS

D-1 Recovery Efficiency by 5 μm Pore Size, 142 mm Polycarbonate Membrane Filters

Several tests were conducted to determine the recovery efficiency of the membrane filters and sampling techniques used to concentrate *Giardia* samples. Table D-1 summarizes the test results; the data in this table was developed by Dr. Hibler and the complete test procedures and results are included in "Removal of *Giardia lamblia* from Water Supplies," in Appendix J (Bellamy, 1982).

The tests were conducted to determine if there was a difference in recovery resulting from different cyst sources or resulting from different sampling techniques. Tests 1 and 2 in Table D-1 compared different cyst sources and Tests 2 and 3 compared differences in sampling techniques, i.e., pumping the sample through the membrane filter or sucking the sample through.

These results demonstrate that the variation in recovery of *Giardia* cysts is a function of the cysts and not the sampling techniques. Test 1 results range from 36 to 54 percent and average 44 percent. Test 2 results (using a different source of cysts) produced recovery results ranging from 74 to 89 percent and averaged 79 percent. This demonstrated the marked effect the cyst source has on recovery. Comparing Tests 2 at 79 percent recovery to Test 3 at 81 percent recovery demonstrates the minor variation caused by different sampling techniques.

Tests which complement these results are those which are performed routinely on the filter feed tank during *Giardia* cyst test runs. Table D-2 summarizes the recovery information developed during the slow sand filter tests. Each of these tests represents a different cyst source. Again large variations in recovery, i.e., 18 to 80 percent result when different cysts sources were tested, thus confirming the dependence of recovery on the "state" of the cyst.

The "state" of the cyst and its resultant behavior during the sampling procedure is probably dependent on a number of factors. But, based on our observations and Dr. Hibler's experience, the two most apparent factors are: 1) the source of the cysts, and 2) the age of the cysts.

Based on these results and conclusions it became apparent that the membrane recovery factor should be determined for each test run and that an average recovery for all test runs should not be used. When a membrane

Table D-1. Cyst concentration by membrane filter sampling compared cyst concentration in source tank as determined by grab sample. Analysis by micropipette technique for both sampling methods. Tests conducted in laboratory of Dr. Charles Hibler, July 1982.

Test Condition and Technique	Run Number	Cyst Concentration Based Upon Grab Sample of Tank (cysts/liter)	Cyst Concentration Resulting from Given Test Condition in the First Column (cysts/liter)	Recovery (%)
1. Cysts concentrated with a pump and membrane filter (cyst batch 1)	1	3,333	1,200	36
	2	3,333	1,800	54
	3	3,333	1,500	45
	4	3,333	1,300	39
	5	3,333	1,550	46
	Average	3,333	1,470	44
2. Cysts concentrated with a pump and membrane filter (cyst batch 2)	1	35,000	25,000	71
	2	35,000	30,000	86
	3	35,000	27,000	77
	4	35,000	26,000	74
	5	35,000	31,000	89
	Average	35,000	27,800	79
3. Cysts concentrated with a membrane filter and vacuum, i.e., no pump (cyst batch 2)	1	35,000	26,000	74
	2	35,000	31,000	89
	3	35,000	28,000	80
	Average	35,000	28,300	81

Table D-2. Comparison of cysts recovered by sampling milk cooler feed tank water using membrane filters with cyst concentrations in tank as computed after adding cyst concentrate suspension. Analyses performed during slow sand filter experiments.

Slow Sand Filter Run Number	Cyst Concentration[1] in Filter Feed Tank	Cyst Concentration Determined by Subsampling the Filter Feed Tank with a Membrane Filter[2]	Membrane Filter Percent Recovery
48	420	196.8	46.8
60	500	399.3	79.9
66	50	35.8	71.7
69	50	31.3	62.6
75	50	15.9	31.8
81	50	32.2	64.3
87	1,000	183.8	18.4
90	1,000	221.0	22.1

[1] Each of these results are the average of 3 to 6 analyses performed on a cyst concentrate of liquefied dog feces which is added to the filter feed tank on a batch basis. Cyst concentration equals a number of cysts in concentrate suspension divided by volume of water in tank.

[2] Each of these results are the average of 4 to 11 analyses. The samples are concentrated with a membrane filter.

recovery factor for a particular run cannot be calculated, e.g., no influent sample was taken, an average from similar tests has been used.

The mathematical determination of the membrane recovery factor is:
100 x (detected cyst conc.)/(known ("added") cyst conc.)

The known ("added") cyst concentration is determined by analyzing a cyst concentration, i.e., liquified dog feces, numerous times, then adding the concentrate to the batch filter feed tank and adjusting the concentration by the appropriate dilution factor. The detected cyst concentration is then detemined by analyzing a sample from the filter feed tank. This sample is concentrated with a membrane filter thus allowing for the membrane recovery calculation. The membrane filter recovery factors in Table D-2 were determined this way.

D-2 Detection Limit Determinations

There are two detection limit calculations used for this experimentation: 1) for each individual micropipette analysis, and 2) for an average detection limit when numerous samples are being considered. Each of these methods are discussed below.

D-2-1 Micropipette detection limit

The micropipette method of analysis begins by concentrating a sample to one milliliter. A 0.05 mℓ (1/20) aliquot is then taken and microscopically examined. This accounts for the first detection limit factor of: (20)/(Number of aliquots examined). The total detection limit for a sample on a per liter basis is then calculated by:

[(20)/Number of aliquots]/[(Fractional membrane recovery)(liters of sample concentrated)]

This equation accounts for the analysis dilution, the membrane filter recovery, and the size of sample. For example:

Sample size = 100 liters
Membrane recovery = 45%
One aliquot analyzed
Detection limit = [(20/1)]/[(0.45)(100)] = 0.44 cyst/liter

The average detection limit is used when more than one analysis has been performed for a test run. Rather than physically combining all of the samples into one container and performing one analysis, each sample was analyzed separately and then the results were mathematically combined. This leads to slightly different results but both results are valid. The mathematical approach requires an averaging of detection limits since individual detection limits are not suitable for multiple analyses of the same source. For example, a single source of water is analyzed 100 times for coliforms and none are found in any of the 100 ml samples. The true test accuracy is not demonstrated by reporting the individual test detection limits, i.e. that the source has less than one coliform per 100 ml, when in fact 10 liters of sample were analyzed and no coliforms were found.

The individual detection limit for Giardia analyses is based on the probability of finding one cyst. This can be understood by envisioning the analysis of a thousand 1 ml samples, each having one cyst in them. If one .05 ml aliquot is taken from each sample and examined it will be determined, after completing all of the analyses, that there is a one in twenty chance of finding a cyst. The detection limit for each analyses was <20/1 ml or the inverse of the probability of finding one cyst i.e. 1/20. This factor of 20 is the multplication factor already discussed.

Since the detection limits are the inverse of the probabilities of finding a cyst it is then appropriate to apply probability calculations to multiply analyses when determining the combined detection limit. The following calculations describe the analysis:

P = Probability of finding one cyst
N = Number of tests
$(1-P)$ = Probability of not finding a cyst
$(1-P)^N$ = Probability of not finding a cyst in N samples
$1-(1-P)^N$ = Probability of finding a cyst in N samples
$1/[1-(1-P)^N]$ = Detection limit for N tests, i.e. inverse of probability of finding a cyst

For example, assume 5 samples were collected with an average membrane recovery factor of 50 percent and that each sample was concentrated from 10 liters.

Individual detection limits = (20 cysts/1 aliquot)/(0.5, membrane recovery factor) = 40 cysts
(only one aliquot was analyzed)
Individual probability of detecting one cyst = 1/40
Average detection limit for the 5 tests = $1/(1-(1-1/40)^5]$
= 8.41 cysts
Average detection limit per liter = 8.41/10 = 0.841 cysts/liter

As an alternative the 5 samples in the above example could have been physically combined and the detection limit would have been:

Individual detection limit = (20/1)/0.5 = 40 cysts
(only one aliquot was analyzed)
Individual detection limit per liter = 40 cysts/50 liter
= 0.8 cysts/liter

This result, as expected, is somewhat lower than the mathematical combination, but for each technique the detection limit is valid.

Detection limits in this report can be for individual analyses or an average for a test run; each is applied to its specific case. An average detection limit is not applied to an individual analysis.

D-3 Conclusions

The counting and sampling experiments conducted in July, August and September of 1982, established that the micropipette technique is the most suitable technique for this work. Different samples from the same suspension, different replicates of the sample, and three persons counting resulted in a maximum difference between any two counts of only about fifteen percent. Although there is no suspension of known cyst concentration to use for a standard, it is believed that the counts by this technique represent the *Giardia* cyst population in the sample counted.

On sampling efficiency, the use of the 5 μm pore size, 142 mm polycarbonate membrane filter represents the best state-of-the-art on sampling at this time. Sampling efficiency of the pump membrane filter system was determined to be primarily dependent on the source and age of cysts being used for a particular experiment. This discovery resulted in the determination of a cyst recovery factor from the membrane filters on a test run by test basis.

APPENDIX E

RAW DATA TABLES FOR DIATOMACEOUS EARTH FILTRATION EXPERIMENTS

Table E-1. Master table of raw data obtained from laboratory tests for diatomaceous earth filtration experiments. Location at Engineering Research Center using Horsetooth Reservoir water.

IDENTIFICATION		TEST CONDITIONS					MEASUREMENTS											
							Total Coliform		Standard Plate Count		Giardia			Turbidity		Particle Counts from 6.35 to 12.67 µm	
Date	Run Number	Diatomaceous Earth Grade	Temperature (°C)	Filtration Rate (m/hr)	Time From Start of Run (min)	Pressure (cm Hg)	Influent (coliform/100mL)[14]	Effluent (coliform/100mL)[14]	Influent (colonies/1mL)[14]	Effluent (colonies/1mL)[14]	Added (cysts/liter)[14]	Detected[1] (cysts/liter)[14]	Effluent Sample[2] (No.)	Influent (NTU)	Effluent (NTU)	Influent (count/10 ml)	Effluent (count/10 ml)
7/4/82	13	C-545	5	2.44	30	6.2	5.2	8	1975	308	100	27.7		3.5	3.3	831	67
					60	6.2									3.3		
					90	6.2	5.9	18	1555	287			0		3.3		7
7/26/82	18	C-545	13	2.44	30	8.2	ND[3]		9700	2570	100	50.5		4.2	3.6	776	24
					60	8.2									3.7		
					90	8.3			9900	2360			0		3.6		139
7/27/82	20	C-545	5	2.44	30	8.0	37000	15,000	48,000	10,700	500	229.0		4.4	3.6	2447	79
					60	8.0									3.5		
					90	8.0	23000	18,000	41,000	21,900			0		3.5		77
7/30/82	28	C-545	5	2.44	30	7.3	35,000	15,000	79,000	19,900	770	75.0		4.6	3.8	3280	205
					90	7.3									3.8		
					120	7.3		28,000		39,900					3.9		261
					150	7.3									3.8		
					210	7.3		33,000		49,000			0		3.8		72
					270	7.4									3.8		
					300	7.4		24,000		54,000					3.8		64
					370	7.4	33,000	28,000	66,000	64,000			0		3.8		81
8/26/82	41	C-545	12	2.44	15	ND	ND		ND		33,600	ND	0	ND		ND	
					25								0				
					35								0				
					40								0				
					45								300				
					50								600				
					55								800				
9/30/82	42	C-545	13	2.44	20	11.5	ND		ND		10,000	ND				ND	
					50								0				
					100	13.5							0	9.1	6.9		
					160								0				
10/5/82	43	C-545	15	2.44	30	7.4	ND		ND		5460	ND		ND		ND	
					60								0				
					95								0				
					160	8.4											
					340								0				
10/12/82	45	C-545	14	2.44	30	7.4	ND		ND		8,850	ND			ND	ND	
					60	ND							0				
					90	8.6							0				
					270[4]	9.0							0	6.6			
					310	19.2							0				
10/14/82	46	C-545	16.0	2.44	60	7.8	2600	2800	17,550	7800	0			7.7	7.0	ND	
					120	7.8		4050		9850				7.6	6.8		
					180	7.9		3000		9400				7.7	6.7		
					240	8.4	14,600	3300	12,050	6050				7.7	6.8		
					300	8.4		4000		ND				7.7	6.8		
					360	8.4	12,300	4050	17,300	6250				7.7	6.8		

Table E.1. Continued.

IDENTIFICATION		TEST CONDITIONS					MEASUREMENTS										
							Total Coliform		Standard Plate Count		Giardia			Turbidity		Particle Counts from 6.35 to 12.67 µm	
Date	Run Number	Diatomaceous Earth Grade	Temperature (°C)	Filtration Rate (m/hr)	Time From Start of Run (min)	Pressure (cm Hg)	Influent (coliform/100ml)^{14}	Effluent (coliform/100ml)^{14}	Influent (colonies/1ml)^{14}	Effluent (colonies/1ml)^{14}	Added (cysts/liter)^{14}	Detected^{1} (cysts/liter)^{14}	Effluent Sample^{2} (No.)	Influent (NTU)	Effluent (NTU)	Influent (count/10 ml)	Effluent (count/10 ml)
7/14/82	14	C-545	5	4.88	30	12.1	52	20	1975	464	100	44.6		3.5	3.4	669	36
					60	12.4								3.6	3.4		
					90	12.5	59	20	1555	470			0	3.5	3.4		22
7/26/82	19	C-545	13	4.88	30	16.5	ND			9700	100	65.9		4.4	3.6	776	40
					60	15.0								3.6			
					90	15.5			9900	6080			0	3.6		42	
7/27/82	21	C-545	5	4.88	30	14.8	37,000	20,000	48,000	22,000	500	330.0		4.4	3.6	2447	228
					60	14.9								3.6			
					90	15.0	23,000	19,000	41,000	10,800			0	3.6		63	
7/26/82	17	C-545	5	9.76	30	30.5	ND		8300	2800	100	47.0		4.2	3.8	1003	70
					60	31.5								3.7			
					90	32.5				4320			0	3.6		63	
7/28/82	26	C-545	5	9.76	30	28.0	4800	3700	7700	3210	500	31.5		4.2	3.8	696	53
					60	28.2									3.8		
					90	28.6		3300		4270			0		3.7		32
11/18/82	60	C-545	16.0/10.5^{5}	2.44	80	7.9	ND		ND		2467^{6}	ND		9.9/9.6^{7}	8.6	ND	
					140	8.0									8.4		
					200	8.1									8.3		
					260	8.9					2467				8.6		
					320	8.9									8.6		
					380	9.2									8.4		
					440	9.2					2467		0		8.2		
					500	9.2									8.4		
					560	-									8.3		
					740	13.8					2467				8.2		
					980	19.5							0		8.2		
8/12/82	37	C-545	11.0	2.44	30	8.3	ND		ND		21x10^{6}	ND	ND^{8}	ND		ND	
7/14/82	15	C-535	5	2.44	30	6.6	36	<1	1750	259	100	45.5		3.6	3.2	771	44
					60	6.6									3.2		
					90	6.6	27	16	2300	840			0		3.2		26
7/16/82	16	C-535	5	4.88	30	13.1	36	2	1750	259	100	45.5		3.6	3.1	662	98
					60	13.2									3.1		
					90	13.3	27	4	2300	840			0		3.1		102
7/13/82	13	C-503	5	2.44	30	6.6	36	<1	1950	33	100	76.4		3.5	3.3	909	2101^{10}
					60	6.6									3.3		
					90	6.6	19	<1	2910	85			0		3.3		467
7/27/82	23	C-503	13	2.44	30	7.3		1700		3500	100	ND^{9}	ND	4.3	3.5	865	31
					60	7.3									3.6		
					90	7.3	6100	2100	7300	2900					3.6		296
7/28/82	25	C-503	5	2.44	30	7.9	36,000	8800	95,000	20,000	500	127.0		4.4	3.7	2512	16
					60	7.9									3.8		
					90	7.9	30,000	9800	55,000	25,800			0		3.7		18
10/7/82	44	C-503	15	2.44	30	7.8	ND		ND		5460	ND	0	ND		ND	
					100	9.0							0				
					205	9.7							0				

IDENTIFICATION		TEST CONDITIONS					MEASUREMENTS										
							Total Coliform (coliform/100ml)[14]		Standard Plate Count (colonies/1ml)[14]		Giardia			Turbidity (NTU)		Particle Counts from 6.35 to 12.67 μm (count/10 ml)	
Date	Run Number	Diatomaceous Earth Grade	Temperature (°C)	Filtration Rate (m/hr)	Time From Start of Run (min)	Pressure (cm Hg)	Influent	Effluent	Influent	Effluent	Added (cysts/liter)[14]	Detected[1] (cysts/liter)[14]	Effluent Sample[2] (No.)	Influent	Effluent	Influent	Effluent
10/21/82	47	C-503	14.5	2.44	30	12.9	16,000	1750	9,400	3850	0			7.6	7.1	ND	
					60	12.9		2100		2540				7.1			
					120	12.9		2750		5700				7.1			
					180	12.9		3200		6800				7.1			
					210	13.0	13,500	3000	16,600	7750				6.9			
					270	13.1	11,000	2700	8,800	6950				7.6	6.8		
					330	13.1		2800		6850				6.8			
7/13/82	12	C-503	5	4.88	30	12.0	36	<1	1950	11	100	40.0		3.6	3.3	871	49
					60	12.1								3.3			
					90	12.2	19	<1	2910	277			0	3.3		45	
7/27/82	22	C-503	13	4.88	30	15.1	4800	2500	9200	2755	100	59.0		4.2	3.6	865	64
					60	15.2								3.7			
					90	15.3	6100	3200	7300	10600[12]			0	3.6		18	
7/28/82	24	C-503	5	4.88	30	13.7	34,000	11,400	95,000	19,000	500	127.0		4.3	3.5	2188	178
					60	13.9								3.6			
					90	14.2	38,000	26,000	55,900	34,900			0	3.5		45	
7/28/82	27	C-503	13	9.76	30	30.9	6000	3400	10,200	4600	100	33.0		4.2	3.7	778	21
					60	31.5								3.7			
					90	32.3		3100		3330			0	3.6		124	
8/6/82	32	C-503	13	2.44	30	7.8	3850	1000	9000	3015	0			4.6	4.1	ND	
					90	7.8		1700		2765				4.2			
					150	7.8		2000		2805				4.1			
					210	7.8	5050	1900	4200	3465				4.1			
					270	7.9		1600		2195				4.0			
					330	7.9		310		3370				4.0			
7/12/82	9	Hyflo	5	2.44	30	6.9	41	<1	1990	158	100	41.4		3.7	3.0	732	278
					60	7.0								2.9			
					90	7.0	37	<1	1900	83			0	3.0		47	
7/12/82	10	Hyflo	5	4.88	30	12.0	37	<1	1900	4	100	22.2		3.6	3.1	744	28
					60	12.0								3.5	3.1		
					90	12.1	38	<1	2100	31			0	3.5	3.1		17
8/3/82	29	Hyflo	12.0	2.44	30	9.2	ND		4900	2000	0			4.5	3.7	ND	
					90	9.2				5900				4.5	3.6		
					150	9.3				6400				4.6	3.6		
					210	9.3				4600				4.6	3.6		
					270	9.4			9800	2200				4.6	3.6		
					330	9.4				4200				4.6	3.7		
8/5/82	31	Hyflo	13.0	2.44	30	9.9	4000	440	8600	4900	0			4.6	3.7	ND	
					90	9.9		600		4700					3.8		
					150	9.9		700		2990					3.8		
					210	9.9	4000	740	9500	3600					3.8		
					270	9.9		830		1980					3.7		
					330	10.0		800		585					3.7		

Table E.1. Continued.

IDENTIFICATION		TEST CONDITIONS					MEASUREMENTS										
							Total Coliform		Standard Plate Count		Giardia			Turbidity		Particle Counts from 6.35 to 12.67 µm	
Date	Run Number	Diatomaceous Earth Grade	Temperature (°C)	Filtration Rate (m/hr)	Time From Start of Run (min)	Pressure (cm Hg)	Influent (coliform/100ml)[14]	Effluent (coliform/100ml)[14]	Influent (colonies/1ml)[14]	Effluent (colonies/1ml)[14]	Added (cysts/liter)[14]	Detected[1] (cysts/liter)[14]	Effluent Sample[2] (No.)	Influent (NTU)	Effluent (NTU)	Influent (count/10 ml)	Effluent (count/10 ml)
8/9/82	33	C-512	15.0	2.44	30	11.5	900	<10	5300	430	0			4.9	3.3	ND	
					90	11.9		<10		480				4.9	3.3		
					150	12.4		<10		750				4.9	3.3		
					210	13.0	1200	10	3200	710				4.9	3.2		
					270	13.7		<10		1210				4.9	3.2		
					330	14.2		20		2100				4.9	3.1		
8/11/82	35	C-512	14.0	2.44	30	12.1	3800	13	2900	670	0			4.6	3.3	ND	
					90	12.5		44		630				3.3			
					150	13.0		49		740				3.3			
					210	13.5	960	94	4300	810				3.3			
					270	14.1		110		260				3.3			
					330	14.5		116		1310				3.3			
8/4/82	30	STANDARD SUPER CEL	13.0	2.44	30	17.0	6200	<1	8200	150	0			4.5	2.3	ND	
					90	19.2		<1		260				2.3			
					150	20.7		<1		600				2.3			
					210	22.5	6000	<1	10300	490				2.3			
					270	24.5		1		280				2.2			
					330	26.2		5		240				2.2			
8/18/82	38	STANDARD SUPER CEL	11.0	2.44	30	17.8	32,500	ND	2,955,000	ND	0			5.0	2.5	ND	
					45			87.0		75							
					85	19.2		74.0		57				2.5			
					95			67.5		58							
					145	21.7		61.5		59				2.6			
					205	24.2		38.5		77				2.5			
					265	26.5		50.0		75				2.6			
					295			41.5		68							
					325	28.8		44.0		62				2.6			
					355			44.5		98							
					403	31.6		34.0		95				2.5			
8/19/82	39	STANDARD SUPER CEL	12.0	2.44	30	15.8		11.5		13	0			5.1	2.6	ND	
					90	18.0	<10,000	11.0	6200	44				5.1	2.6		
					150	21.0		5.5		59				5.1	2.6		
					210	23.0		6.5		73				5.1	2.6		
					270	26.9		6.5		112				5.1	2.5		
					330	29.4		12.5		158				5.1	2.4		
					390	33.7		14.0		197				5.2	2.2		
					465	37.7		17.0		254				5.2	2.2		
					480	ND	<10,000	ND	10200	ND				ND	ND		
					510	44.0		123.5		245				5.2	2.1		
					570	49.9		23.0		255				5.2	1.9		
					630	54.5		30.0		400				5.2	1.9		
8/10/82	34	FILTER CEL	14.5	2.44	30	73.9[10]	960	<1	3850	<1	0			4.6	0.13	ND	
					90	129.8		<1		3				4.6	0.12		
					110	ND	750	ND	4050	1				ND	ND		
					115	158.2		ND		ND				4.6	0.10		

Table E.1. Continued.

IDENTIFICATION		TEST CONDITIONS					MEASUREMENTS										
							Total Coliform		Standard Plate Count		Giardia			Turbidity		Particle Counts from 6.35 to 12.67 µm	
Date	Run Number	Diatomaceous Earth Grade	Temperature (°C)	Filtration Rate (m/hr)	Time From Start of Run (min)	Pressure (cm Hg)	Influent (coliform/100ml)[14]	Effluent (coliform/100ml)[14]	Influent (colonies/1ml)[14]	Effluent (colonies/1ml)[14]	Added (cysts/liter)[14]	Detected[1] (cysts/liter)[14]	Effluent Sample[2] (No.)	Influent (NTU)	Effluent (NTU)	Influent (count/10 ml)	Effluent (count/10 ml)
8/11/82	36	FILTER	13.0	2.44	30	78.1	560	<1	1140	0.5	0			5.4	0.10	ND	
		CEL			60	107.5	*	<1		3.5					0.10		
					90	132.4	720	<1	840	3.5					0.14		
					120	158.2		<1		3.0					0.13		
11/5/82	48	C-545	19.0	2.44	15	11.7	4750	0	20750	5	0			8.0	0.04	ND	
		4% Alum			30	12.5		6		35				8.0	0.11		
		25 PPM			45	14.9								8.0	0.94		
		BODYFEED			60	16.8		32		670				8.0	1.34		
					75	19.1								8.0	1.47		
					90	20.8		40		1645				8.0	1.57		
					105	22.8								8.0	1.47		
					120	24.7	2150	63	31,500	2200				8.0	1.41		
					135	26.5								8.0	1.32		
					150	28.5		62		3250				8.0	1.20		
11/20/82	50	C-503	14.5	2.44	15	12.8	4750	1.5	750	7.5	0			9.5	0.06	ND	
		5% Alum			30	13.7		6.0		50.5					0.64		
		25 PPM			45	14.6									1.89		
		BODYFEED			60	15.7		16.0		84.5					2.20		
					75	17.0									2.30		
					90	17.5		55.0		168.0					2.30		
					105	18.6								9.5	2.30		
					120	20.3		104.0		111.0					2.40		
					150	23.6	5200	165.0	750	265.0					2.50		
					180[11]	26.6		155.0		95.0					2.50		
					195	27.9									2.40		
					210	29.5		115.0		225.0				9.5	2.30		
					225	31.4									2.20		
					240	33.1		140.0		ND					2.10		
					255	35.0									2.00		
					270	36.9		215.0		300					1.99		
					285	38.8									1.92		
					300	41.4		115.0		245				9.5	1.81		
12/2/82	51	C-545	13.5	2.44	0		5100		2240		0			9.4		ND	
		5% Alum			15	16.4		<1		3.5					0.05		
		25 PPM			30	18.3		<1		8.0					0.05		
		BODYFEED			45	20.5									0.08		
					60	24.0		4		22.0					0.11		
					75	27.5									0.21		
					90	29.6		8		97.5					0.23		
					105	32.7								9.4	0.25		
					120	35.0	6500	9	6000	94.0					0.23		
					135	38.3									0.21		
					150	40.3		5		86.5					0.19		
					180	51.2									0.16		
					210	60.7		17		104.5					0.14		
					240	71.9									0.13		
					270	84.7									0.12		
					300	97.5		20		>3000				9.4	0.12		

Table E.1. Continued.

IDENTIFICATION		TEST CONDITIONS					MEASUREMENTS										
							Total Coliform		Standard Plate Count		Giardia			Turbidity		Particle Counts from 6.35 to 12.67 μm	
Date	Run Number	Diatomaceous Earth Grade	Temperature (°C)	Filtration Rate (m/hr)	Time From Start of Run (min)	Pressure (cm Hg)	Influent (coliform/100ml)^{14}	Effluent (coliform/100ml)^{14}	Influent (colonies/1ml)^{14}	Effluent (colonies/1ml)^{14}	Added (cysts/liter)^{14}	Detected^1 (cysts/liter)^{14}	Effluent Sample^2 (No.)	Influent (NTU)	Effluent (NTU)	Influent (count/10 ml)	Effluent (count/10 ml)
12/8/82	52	C-503	13.5	2.44	0		6150		2160		0			9.5		ND	
		5% Alum			15	16.3									0.03		
		25 PPM			30	18.0		1.5		7.0					0.06		
		BODYFEED			45	19.8									0.15		
					60	21.7		14.0		25.0					0.48		
					75	23.5									1.10		
					90	25.6		44.5		282.5					1.22		
					105	28.1								9.5	1.11		
					120	30.9	7750	43.0	2395	>30,000^{12}					0.76		
					135	33.9									0.57		
					150	37.7									0.45		
					165	42.5									0.38		
					180	46.9		50.5		300.0					0.34		
					210	57.7								9.5	0.25		
12/8/82	53	C-503	13.5	2.44	0		6150		18,750		0			9.8	0.04	ND	
		5% Alum			15	17.8									0.08		
		50 PPM			30	22.1									0.11		
		BODYFEED			45	27.2									0.19		
					60	31.5									0.23		
					75	35.5									0.21		
					90	40.6		>250		90.5				9.8	ND		
					120	ND									0.16		
					150	51.7									ND		
					180	ND									0.11		
					195	65.4									ND		
					210	ND									0.11		
					240	78.8		17.5		ND				9.8	0.10		
					255	86.4									0.13		
					270	95.0									ND		
					300	108.6		21.5		72.5					0.17		
12/18/82	54	C-503	12.5	2.44	0		7100		27,200		0			11.0		ND	
		8% Alum			15	30.6									0.03		
		25 PPM			30	36.6									0.06		
		BODYFEED			45	41.7									0.07		
					60	49.2									0.11		
					75	56.2									0.14		
					90	62.8									0.14		
					105	69.4									0.22		
					120	78.2		13		172				11.0	0.28		
					135	87.9									0.28		
					150	96.5									0.22		
					165	106.8									0.16		
					180	116.8		19		209					0.11		
					195	129.2									0.10		
					210	141.6									0.08		
					225	152.5									0.06		
					240	163.9		4		12				11.0	0.05		

Table E-1. Continued.

IDENTIFICATION		TEST CONDITIONS					MEASUREMENTS										
							Total Coliform		Standard Plate Count		Giardia			Turbidity		Particle Counts from 6.35 to 12.67 µm	
Date	Run Number	Diatomaceous Earth Grade	Temperature (°C)	Filtration Rate (m/hr)	Time From Start of Run (min)	Pressure (cm Hg)	Influent (coliform/100ml)[14]	Effluent (coliform/100ml)[14]	Influent (colonies/1ml)[14]	Effluent (colonies/1ml)[14]	Added (cysts/liter)[14]	Detected[1] (cysts/liter)[14]	Effluent Sample[2] (No.)	Influent (NTU)	Effluent (NTU)	Influent (count/10 ml)	Effluent (count/10 ml)
12/19/82	55	C-545	12.5	2.44	0		ND		ND		0			10.0		ND	
		5% Alum			15	13.7									0.10		
		0 PPM			30	15.1									1.12		
		BODYFEED			45	16.0									2.2		
					60	16.5									2.8		
					75	17.3									3.2		
					90	17.8									3.4		
					105	18.1									3.9		
					120	19.1								10.0	4.0		
					135	19.5									4.0		
					150	20.0									4.1		
					165	20.5									4.2		
					180	21.0									4.3		
					195	21.5									4.4		
					210	22.0									4.0		
					225	22.6									4.3		
					240	23.6								10.0	4.5		
12/19/82	56	C-545	13.5	2.44	0		ND		ND		0			9.7		ND	
		5% Alum			15	12.1									7.3		
		BODYFEED			30	12.3									4.5		
		0% Alum			45	13.6									4.6		
		PRECOAT			60	14.8									4.2		
					75	16.9									3.6		
					90	21.0									3.2		
					105	21.0									3.2		
					120[13]	ND									ND		
12/20/82	57	C-545	12.5	2.44	0		ND		ND		0			9.5		ND	
		2% Alum			15	12.8									1.65		
		25 PPM			30	13.6									3.5		
		BODYFEED			45	14.3									3.5		
					60	15.1									3.5		
					75	15.8									3.5		
					90	16.6									3.4		
					105	17.3									3.3		
					120	18.1								9.5	3.3		
					135	19.0									3.3		
					150	19.6									3.3		
					165	20.3									3.3		
					180	21.0								9.5	3.1		

Table E-1. Continued.

IDENTIFICATION		TEST CONDITIONS					MEASUREMENTS										
							Total Coliform		Standard Plate Count		Giardia			Turbidity		Particle Counts from 6.35 to 12.67 µm	
Date	Run Number	Diatomaceous Earth Grade	Temperature (°C)	Filtration Rate (m/hr)	Time From Start of Run (min)	Pressure (cm Hg)	Influent (coliform/100ml)[14]	Effluent (coliform/100ml)[14]	Influent (colonies/1ml)[14]	Effluent (colonies/1ml)[14]	Added (cysts/liter)[14]	Detected[1] (cysts/liter)[14]	Effluent Sample[2] (No.)	Influent (NTU)	Effluent (NTU)	Influent (count/10 ml)	Effluent (count/10 ml)
1/10/83	58	C-545	12.0	2.44	0		ND		ND		0			9.2		ND	
		5% Alum			15	11.7									7.7		
		BODYFEED			30	11.8									6.7		
		0% Alum			45	12.0									5.9		
		PRECOAT			60	12.8									5.2		
					75	13.8									4.7		
					90	14.7									4.3		
					105	16.8									3.4		
					120	19.9								9.2	3.0		
					135	21.2									2.8		
					150	23.5									2.5		
					165	25.8									2.3		
					180	28.3									2.0		
					195	31.5									1.70		
					210	34.4									1.51		
					225	37.0									1.33		
					240	40.5								9.2	1.25		
					255	43.8									1.17		
					270	49.0									1.22		
					285	53.5									1.22		
					300	58.4									1.21		

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[1] This value is the actual Giardia influent value.
[2] This value is the number of cysts detected in the effluent sample.
[3] No data. This vaue was not measured.
[4] After measurements at 270 minutes flowrate was increased to 2 gpm (4.88 m/hr).
[5] 10.5°C milk cooler containing Giardia, 14.0°C plastic tank containing Horsetooth Reservoir influent.
[6] Average of 2467 cysts/liter added, 2.96×10^6 cysts added intermittently for 80 minutes at 0, 4, 8, and 12 hours after start of run.
[7] Milk cooler containing Giardia, 9.9 NTU turbidity; plastic tank containing Horsetooth Reservoir influent, 9.6 NTU turbidity.
[8] Giardia slug test run discontinued after 30 minutes. No measurements were taken
[9] No Giardia cysts were found in the influent sample. Effluent Giardia cyst measurement was not counted.
[10] Pressure readings for all Filter Cel test runs were measured in psi then converted to cm Hg.
[11] After measurements and readings at 180 minutes the bodyfeed concentration was increased from 25 ppm to 50 ppm.
[12] This value was recorded in raw data but was not used in any computations.
[13] At 120 minutes the run was discontinued due to failure of the bodyfeed pump.
[14] The use of significant figures does not imply accuracy; they are used to permit the tracing of calculations.

Table E-2. Master table of raw data obtained from field tests for diatomaceous earth filtration experiments located at Cachela Poudre River, Fort Collins Water Treatment Plant No. 1 and at Dillon Water Treatment Plant.

IDENTIFICATION			TEST CONDITIONS				MEASUREMENTS										
							Total Coliform (org/100 mL)		Standard Plate Count (colonies/mL)		Giardia Cysts			Turbidity		Particle Count	
Date	Run Number	D.E. Grade	Temperature (°C)	Filtration Rate (m/m)	Time from Start of Run (min)	Pressure (cm Hg)	Influent	Effluent	Influent	Effluent	Added (cysts/L)	Detected (cysts/L)	Effluent Sample (No.)	Influent (NTU)	Effluent (NTU)	Influent (count/100 mL)	Effluent (count/100 mL)
4/17/83	F1 Poudre	C-545	10	2.44	25	16.5	100		35,000		3950	ND		3.7		ND	ND
					55										0.95		
					80								0				
					85			5		9500					1.02		
					130								0				
					145	16.5		1		2000							
4/23/83	F2 Poudre	C-545	9	2.44	30	18.6	7000	2000	26500	3000				32.0	12.3	ND	ND
					60	28.8											
					90	38.8		1000		4050					6.7		
					120	52.0											
					130	59.4											
					135	62.2											
					150	71.5		2000		2950					5.2		
					180	95.8											
					195	108.7											
					210	123.7		1500		3750					5.0		
5/5/83	F3 Dillon	C-545	3.5	2.44	30	0.3	ND	ND	[1]ND	ND		1000	229	0.66	0.51	ND	ND
					90												
					105	3.3							0		0.33		
5/6/83	F4 Dillon	C-545	3.5	9.76	30	33.0	3500		1100		500	312		0.58	0.33	ND	ND
					60												
					75	43.0		1500		900			0		0.35		
5/6/83	F5 Dillon	C-545	3.5	4.88	30	11.8	2500	1500	1075	600	1000	740		0.55	0.42	ND	ND
					90	14.0		1400		1000			0		0.44		
5/6/83	F6 Dillon	C-545	3.5	2.44	30	8.0	3500	ND	6000	1300	7400	2278		2.4	2.2	ND	ND
					65	8.8		1000		750			0		0.72		
5/7/83	F7 Dillon	C-545	3.5	2.44	30	9.8	1600	335	395	62.5	0			0.76	0.48	ND	ND
					90	10.0		880		80.0					0.73		
					150	10.4	2150	2400	420	1470.0					0.84		
					210	10.6		650		243.5				0.96	0.82		
					270	10.8		5550		2680.0					0.52		
					300	11.0		1750		178.5					0.68		

1/A leak was discovered after this test and the Giardia data deleted.

APPENDIX F

MINERAL ANALYSIS OF TURBIDITY PARTICLES BY X-RAY DIFFRACTION[1/]

I brought back to Ames for analysis four 0.2 micrometer Millipore filters which were used to filter samples of water from the Horsetooth Reservoir as follows:

Sample No.	Source	Amt. Filtered
	Reservoir water filtered through	
1A	1.0 m AMF Cuno Micro-Wynd II	185 ml
1B	filter cartridge and then the	165 ml
	0.2 µm Millipore	
2A	Horsetooth Reservoir water	195 ml
2B	filtered through a 0.2 µm Millipore	200 ml

Note that the water filtered through the 1.0 µm Cuno prefilter removed material that reduced the ability to get water through the 0.2 micrometer Millipore.

At Ames, the ERI - Materials Research Lab processed the samples for me with the following results:

1. Figure 1 shows the x-ray pattern caused by a new Millipore filter (1.2 µm) so that we could subtract the effect of the membrane from the effect of the membrane plus the suspended solid retained on it.

2. Figure 2 shows the x-ray pattern caused by sample 2b (the non-prefiltered reservoir water). The two peaks at 8.8 and 12.3 indicate the presence of Illite and Kaolinite, respectively.

3. Figures 3 and 4 show the x-ray patterns caused by samples 1b and 1a, respectively (the prefiltered reservoir water). The peaks at 12.3 indicate once more the presence of kaolinite. The peaks for Illite are still present at 8.8, but are reduced, indicating that the illite particles are larger and probably more effectively removed by prefiltration.

[1/] Personal communication from E. R. Baumann to D. W. Hendricks, August 12, 1984.

4. Samples 1B and 2B were prepared for study on the SEM by sputtering them with about 200 A of gold. Then, a photomicrograph of representative sections of the 0.2 μm Millipore filter were taken at magnificiations of 1,000X and 5,000X.

   Note: The 1B samples (Exposure No. 1) contain some particles (diatoms) that have a diameter of 8 to 9 μm even though the sample was prefiltered through a 1.2 μm Cuno (?). The 1B samples (Exposure No. 2) at 5000X shows typical clay particles with a length in the range of 3 to 6 μm. A lot of these particles look like clays, but there is some other debris.

   The 2B samples (Exposure No. 3) contain solids that ae about 2 - 4 μm in size and look like clay particles. The 2B samples (Exposure No. 4) contain solids that look like clay and have sizes of 2 to 6 μm, with lots of smaller (much) particles. The larger particles would not significantly contribute to filter clogging as compared to the smaller particles (0.5 μm).

5. We also used the elemental analysis capacity of the SEM to produce the pattern from the 1B and 2B samples. Note that the element pattern for sample 1B (Figure 5) shows the presence of aluminum, silica, gold (from sputtering), potassium, calcium and iron. These are summarized in Figure 6. These are indications of presence of aluminosilicates. The elemental analysis for sample 2B shows similar results except that there is far less calcium present (Figures 7 and 8). We hypothesize that removal of potassium associated with the illite means that the prefiltered sample has less K and therefore the Cacium shows up.

Conclusion

There is evidence of the presence of kaolinite, illite and montmorillonite. The illite is removed in large part by prefiltration. The kaolinite and montmorillonite seem to be the fine particles your group has referred to. The montmorrilonite presence has to be accepted because of peak changes in the 2 - 4 range in (Figure 2 - Figure 1). All in all, it looks mainly inorganic which would suggest non-ionic polymer use such as Percol LT-20 on Separan NT-10.

APPENDIX G

PARTICLE ANALYSIS FROM DIATOMACEOUS EARTH FILTRATION TEST

G-1 Particle Counting Protocol

1. Turn on machine and vacuum pump and allow them to warm up for about 30 minutes prior to using. Set calibration channels to correspond with electrolyte concentration.

2. Collect filter samples in 500 ml glass bottles, washed with 0.2 µm filtered, distilled water to make "particle free."

3. Fill a similarly prepared "particle free" sample beaker to 207 ml with sample--either filter sample or blank sample for background count.

4. Add 15 ml of 0.2 µm filtered, 20% NaCl solution to give a 1.5% by weight electrolyte solution.

5. Place sample in Coulter Counter and stir sample with the glass mixer provided until the solution looks homogeneous. Mix slowly to prevent formation of air bubbles.

6. Run sample for 500 seconds. Follow operating instructions in Coulter Counter, Model TA11, Owner's Manual.

7. Print out particle totals from Channels 3-16. Corresponding particle size ranges for each channel are given in Table G-2.

8. Between samples, spray off aperture tube and electrode with a 1.5% by weight NaCl solution, to prepare for next sample.

9. Repeat Steps 3-8 for each sample.

10. Before and after filter samples, run a blank sample of 0.2 µm filtered, distilled water for background counts.

11. After all samples have been counted, switch machine to "manometer mode" and check flow rate of vacuum pump.

12. Turn off machine and vacuum pump and leave electrode and aperture tube submerged in sample beaker to preserve until next use.

Table G-2. Particle count analyses for diatomaceous earth filtration test Runs 9 through 28 (count/10 ml).

Run No.		#13			#18			#20				#28				
Grade		C-545			C-545			C-545				C-545				
Flow (gpm)		1			1			1				1				
Temperature (°C)		5			13			5				5				
Cyst Conc. (cysts/l)		100			100			500				770				
Sample Time (min)	T[2]	30	90	T	30	90	T	30	90	T	T	30	90	180	270	340
Size Range (μm)																
2.52 to 3.17	15044	1262	1094	23187	1776	2900	49765	2794	3603	57202	54810	3630	4336	3708	3808	3729
3.17 to 4.00	5337	338	291	6504	369	945	16096	934	1020	19641	20191	1285	1556	1130	1162	1057
4.00 to 5.04	3204	199	147	3292	124	399	8394	279	427	10752	11634	702	1066	910	865	756
5.04 to 6.35	1328	106	45	1293	45	180	3323	94	131	4199	4313	184	473	205	185	217
6.35 to 8.00	526	31	7	439	14	87	1319	39	34	1785	1758	78	132	40	38	45
8.00 to 10.08	199	23	0	220	4	38	736	23	25	985	947	58	58	18	16	18
10.08 to 12.70	106	13	0	117	6	14	392	17	18	538	546	69	71	14	10	18
12.70 to 16.00	65	8	3	63	3	9	203	16	13	314	327	54	44	6	11	16
16.00 to 20.02	37	1	4	28	4	6	102	7	7	195	164	42	30	10	13	8
20.02 to 25.40	16	1	1	18	6	0	58	3	6	99	93	27	20	8	6	11
25.40 to 32.00	7	0	0	10	3	0	27	0	1	33	48	3	4	1	1	1
32.00 to 40.30	4	0	0	4	0	1	8	0	0	18	24	4	1	0	0	0

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[1] Design cyst concentration

[2] T indicates influent tank sample

Table G-2. continued.

Run No.		#14			#19			#21			#17			#26	
Grade		C-545			C-545			C-545			C-545			C-545	
Flow (gpm)		2			2			2			4			4	
Temperature (°C)		5			13			5			5			5	
Cyst Conc. (cysts/l)		100			100			500			100			100	
Sample Time (min)	T	30	90	T	30	90	T	30	90	T	30	90	T	30	90
Size Range (μm)															
2.52 to 3.17	16877	1053	910	23187	2275	2576	49765	3712	3514	25835	2136	2446	20395	4015	3359
3.17 to 4.00	6025	299	238	6504	539	597	16096	1286	1001	7980	539	631	5514	1047	738
4.00 to 5.04	3368	123	111	3292	165	175	8394	487	374	4088	195	230	2901	374	221
5.04 to 6.35	1175	45	24	1293	57	64	3323	183	140	1654	75	88	1204	133	51
6.35 to 8.00	365	13	6	439	17	18	1319	93	34	590	41	38	384	37	17
8.00 to 10.08	186	10	6	220	16	20	736	55	18	277	20	16	207	8	11
10.08 to 12.70	118	13	10	117	7	4	392	80	11	136	9	9	105	8	4
12.70 to 16.00	62	10	8	63	9	9	203	71	8	57	9	6	52	4	0
16.00 to 20.02	11	1	4	28	6	4	102	38	3	27	7	4	28	4	4
20.02 to 25.40	18	3	1	18	7	3	58	23	0	16	3	4	18	0	3
25.40 to 32.00	8	1	0	10	1	3	27	4	0	10	1	3	8	0	1
32.00 to 40.30	6	0	0	4	0	0	8	1	0	4	0	4	4	0	0

Table G-2. continued.

Run No.	#15			#16			#11			#23			#25		
Grade	C-535			C-535			C-503			C-503			C-503		
Flow (gpm)	1			2			1			1			1		
Temperature (°C)	5			5			5			13			5		
Cyst Conc. (cysts/l)	100			100			500			100			100		
Sample Time (min)	T	30	90	T	30	90	T	30	90	T	30	90	T	30	90
Size Range (μm)															
2.52 to 3.17	16055	365	242	17325	792	866	15374	2606	955	22026	1210	5654	46235	1499	2209
3.17 to 4.00	5675	54	29	5683	329	305	5951	1460	587	6257	262	2048	14555	334	555
4.00 to 5.04	3224	16	13	3389	147	99	3689	1203	409	3261	90	963	7903	55	107
5.04 to 6.35	1204	20	10	1336	86	64	1481	902	233	1320	45	430	3068	22	24
6.35 to 8.00	422	16	16	425	42	30	563	752	173	495	17	165	1203	6	8
8.00 to 10.08	226	14	6	206	36	26	274	724	152	230	10	85	606	4	6
10.08 to 12.70	123	14	4	31	20	46	152	625	142	140	4	44	343	6	4
12.70 to 16.00	89	13	3	80	19	36	80	407	90	62	3	25	192	0	3
16.00 to 20.02	43	6	1	40	7	30	42	221	55	42	0	4	108	3	0
20.02 to 25.40	26	9	3	23	6	17	21	66	21	17	0	1	49	0	1
25.40 to 32.00	10	0	0	11	0	0	11	21	8	7	0	3	30	0	1
32.00 to 40.30	3	1	0	9	1	1	4	4	3	4	0	0	8	1	0

Table G-2. continued.

Run No.		#12			#22			#24			#27	
Grade		C-503			C-503			C-503			C-503	
Flow (gpm)		2			2			2			4	
Temperature (°C)		5			13			5			13	
Cyst Conc. (cysts/l)		100			100			500			100	
Sample Time (min)	T	30	90	T	30	90	T	30	90	T	30	90
Size Range (µm)												
2.52 to 3.17	17091	288	434	72026	2406	2539	46440	3002	3237	21023	2437	4263
3.17 to 4.00	6686	171	266	6257	633	594	14090	874	936	5613	559	1125
4.00 to 5.04	3675	69	72	3261	224	154	7630	371	253	2901	142	398
5.04 to 6.35	1366	13	0	1320	90	37	3042	192	74	1211	44	140
6.35 to 8.00	479	22	8	495	38	16	1257	83	24	406	11	60
8.00 to 10.08	256	13	20	230	16	1	587	42	17	222	6	30
10.08 to 12.70	136	14	17	140	10	1	364	53	6	150	4	34
12.70 to 16.00	89	8	13	62	13	1	178	59	1	83	0	22
16.00 to 20.02	39	10	10	42	8	0	108	28	3	42	1	20
20.02 to 25.40	24	7	7	17	6	1	69	17	1	24	1	7
25.40 to 32.00	14	1	3	7	3	0	22	6	0	10	0	0
32.00 to 40.30	7	0	1	4	0	0	10	3	1	4	0	1

Table G-2. continued.

Run No.	#9			#10			
Grade	C-503			C-503			
Flow (gpm)	1			2			
Temperature (°C)	5			5			
Cyst Conc. (cysts/l)	100			100			
Sample Time (min)	T	30	90	T	T	30	90
Size Range (µm)							
2.52 to 3.17	15846	1677	429	16376	17432	291	264
3.17 to 4.00	5563	661	152	5950	6601	118	108
4.00 to 5.04	3182	398	78	3396	3813	51	64
5.04 to 6.35	1259	263	55	1341	1539	34	34
6.35 to 8.00	412	136	30	419	374	18	13
8.00 to 10.08	206	88	11	190	257	4	4
10.08 to 12.70	114	54	6	85	162	6	0
12.70 to 16.00	41	37	6	50	95	6	1
16.00 to 20.02	21	16	1	17	47	1	1
20.02 to 25.40	13	7	0	14	20	0	3
25.40 to 32.00	7	6	1	11	13	1	0
32.00 to 40.30	1	3	1	7	7	0	0

APPENDIX H

DIATOMACEOUS EARTH FILTRATION USING ALUM AS A COAGULANT

H-1 Alum Coating of J-M Diatomite

The following is a method of preparing a 1% coating for Celite as provided by Manville Corporation:

> For each 50 lbs of desired grade of Celite, add 2.0 lbs of alum $(AL_2(SO_4)3.\ 15H_2O)$ and approximately 1.0 lbs of soda ash (Na_2CO_3).

The alum should be finely ground (alum flour) for quick dissolving.

The mixture of diatomite, alum and soda ash should be slurried in water, preferably 65°F or higher, and the water volume should not exceed one gallon per pound of dry ingredients.

The resulting slurry should be mildly agitated until the alum and soda ash have dissolved. After the coating has been effected, the slurry may be diluted for body feeding purposes. The concentrated slurry (1 lb/gallon) can be used directly for precoating. For a 2% coating, double the amounts of alum and soda ash.

Soda ash is required to enable the dissolved alum to essentially form a coating on the diatomite particle. The optimum pH for this is between 5.0 and 6.5. Therefore, the alum should be added to the diatomite and water slurry first and after it has dissolved, the soda ash should be added. The soda ash should be added slowly and the pH checked shortly after each addition. The point of this is not to exceed a pH of 6.5. Waters that are high in natural alkalinity may not need as much soda ash to produce a stable pH, thus the need to check the slurry pH.

Precoat and bodyfeed operations are the same as for noncoated diatomite. Coated diatomite generally permits removal of finer particles than possible with uncoated diatomite. It is also possible to use a relatively coarse grade of coated diatomaceous earth and get the particle removal associated with much finer grades. Use of the coarser coated grade also generally results in greater throughput before terminal headloss.

H-2 Procedures for Coating Diatomaceous Earth with Alum

The procedures used to coat the diatomaceous earth prior to experimentation are given below.

1. Weight quantity of diatomaceous earth for precoat (90 grams) and bodyfeed (.82 gm/l of slurry at 25 ppm).

2. Place in separate containers, and add enough distilled water to mix.

3. Mix solution continually with a magnetic stirrer.

4. Add liquid alum to diatomaceous earth and distilled water. For a 1 percent alum concentration add 0.07 grams of 17 percent Al_2O_3 liquid concentration. At 11.13 lb/gal density this is equivalent to 0.052 ml of liquid alum per gram of diatomaceous earth. For higher alum concentrations, i.e., 5 percent, add five times as much alum.

5. Allow 5 to 10 minutes of mixing.

6. Using pH paper, measure the pH of this mixture.

7. Bring pH up to 6.5 by adding Na_2CO_3 (soda ash).

8. Weigh out 0.02 grams of Na_2CO_3 for each gram of diatomaceous earth in the mixture. For higher alum concentrations, i.e., 5 percent, measure five times as much Na_2CO_3.

9. Add this quantity of Na_2CO_3 intermittently while checking the pH. The entire quantity of Na_2CO_3 may not be required to bring the pH up to 6.5.

10. Mix for 5 to 10 minutes. This mixture can be made a day or more in advance. Mixing for 5 to 10 minutes prior to use is suggested.

H-3 Protocol for Applying Alum Coated Diatomaceous Earth to Filter

1. Fill filter housing with water.

2. Leave approximately 2 to 3 liters in precoat bucket during recycle.

3. Add precoat mixture of alum coated diatomaceous earth to precoat bucket.

4. Recycle until diatomaceous earth is bridged on filter septum.

5. Bodyfeed batches were made for addition to 10 liters of water. Put 10 liters of water in bodyfeed tank.

6. Add bodyfeed mixture to bodyfeed tank. This provides 25 ppm bodyfeed at desired alum concentration.

7. Mix until homogeneous.

8. Start bodyfeed addition.

9. Start filtering raw water by opening and closing valves, discontinuing precoat recycle and starting filtration.

10. Take turbidity measurements 15 minutes after raw water feed is begun.

11. Continue routine sampling of turbidity, bacteria, and pressure during test run length.

H-4 Properties for Liquid Alum

CUSTOMER ENGINEERING
Technical Service
Industrial Chemicals Division
P.O. Box 6
Solvay, NY 13209

September 1, 1972

Sheet 1 of 6

A. Physical Properties

1. Description

Liquid alum, an aqueous solution of aluminum sulfate, $Al_2(SO_4)_3$ plus H_2O, is a very pale green liquid. The commerical strength, 36.5° Baume', has 8.3% available Al_2O_3.

2 Physical Constants

Density (gm/cc) at 60°F	1.34
Density (lb/gal) at 60°F	11.2
Gallons/ton at 60°F	180
Viscosity (cp) at 32°F	52
Viscosity (cp) at 70°F	21
Boiling point (°F)	214
Freezing point (°F)	5

3 Conversion from Dry Alum

There are 5.4 pounds of dry alum (17% Al_2O_3) per gallon of liquid alum. Convert dry alum to liquid alum as follows:

$$\frac{\text{pounds dry basis}}{\text{5.4 pounds per gallon}} = \text{gallons liquid basis}$$

H-5 Calcultions Showing Equivalent Chemical Expressions for Alum Concetration by Suing-ill Choi

Accuring to the Allied Data Sheet LA-1, Appendix H-4, the density of the liquid alum is 1.34 gm/ml at 60°F. The data sheet states that the density of dry alum is 5.4 lb dry alum (17 percent Al_2O_3) per gallon of liquid alum. The conversion of these data to concentrations of Al_2SO_4 or Al_2O_3 are not apparent. The conversions are explained as follows:

1. Determine percentage of dry alum in liquid alum solution:

$$\frac{5.4 \text{ lb dry alum}}{\text{gal liquid alum}} \times \frac{\text{gal liquid alum}}{8.34 \text{ lb water} \cdot 1.34 \, \frac{\text{lb liquid alum}}{\text{lb water}}}$$

$$= \frac{4.5 \text{ lb "dry alum"}}{11.17 \text{ lb liquid alum}} = \frac{0.48 \text{ gm "dry alum"}}{\text{gm liquid alum}}$$

2. Deduce form of "dry alum"

The MW of $Al_2(SO_4)_3 \cdot 14H_2O$ is 592

The MW of Al_2O_3 is 102

The Al_2O_3 equivalent weight in $Al_2(SO_4)_3 \cdot 14H_2O$ is $= \frac{102}{592} =$

$$= 0.172 \, \frac{\text{gm } Al_2O_3}{\text{gm } Al_2(SO_4)_3 \cdot 14H_2O}$$

This means that the "dry alum" has the form $Al_2(SO_4)_3 \cdot 14H_2O$. Therefore, there are 0.48 gm $Al_2(SO_4)_3 \cdot 14H_2O$ per gm liquid alum, or

$$\frac{0.48 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}{\text{gm liquid alum}} \times \frac{1.34 \text{ gm liquid alum}}{\text{ml liquid alum}}$$

$$= \frac{0.643 \text{ gm alum as } Al_2(SO_4)_3 \cdot 14H_2O}{\text{ml liquid alum}}$$

3. Equivalent expressions are:

$$[Al^{+++}] = \frac{0.643 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}{\text{ml liquid alum}} \times \frac{54 \text{ gm } Al^{+++}}{592 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}$$

$$= \frac{0.058 \text{ gm } Al^{+++}}{\text{ml liquid alum}} \times \frac{\text{ml liquid alum}}{1.34 \text{ gm liquid alum}}$$

$$Al_2(SO_4)_3 = \frac{0.64 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}{\text{ml liquid alum}} \times \frac{396 \text{ gm } Al_2(SO_4)_3}{592 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}$$

$$= \frac{0.428 \text{ gm } Al_2(SO_4)_3}{\text{ml liquid alum}}$$

$$Al_2O_3 = \frac{0.64 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}{\text{ml liuqid alum}} \times \frac{102 \text{ gm } Al_2O_3}{592 \text{ gm } Al_2(SO_4)_3 \cdot 14H_2O}$$

$$= \frac{0.11 \text{ gm } Al_2O_3}{\text{ml liquid alum}}$$

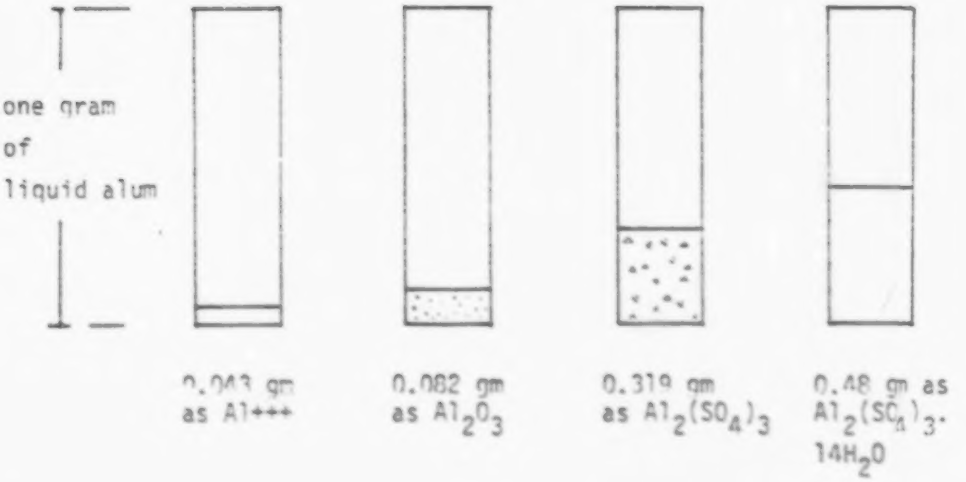
It is possible that operators may express concentrations in terms of mg/ℓ of liquid alum. To do this, the actual weight of liquid alum is used as the basis and is added to water to make one liter of solution. For example, to make 10 mg liquid alum/ℓ solution we find the volume of liquid alum solution that has 10 mg. This is calculated as follows:

$$\frac{X \text{ ml liquid alum}}{10 \text{ mg liquid alum} \times \frac{\text{gm}}{10^3 \text{mg}}} = \frac{1 \text{ ml liquid alum}}{1.34 \text{ gm liquid alum}}$$

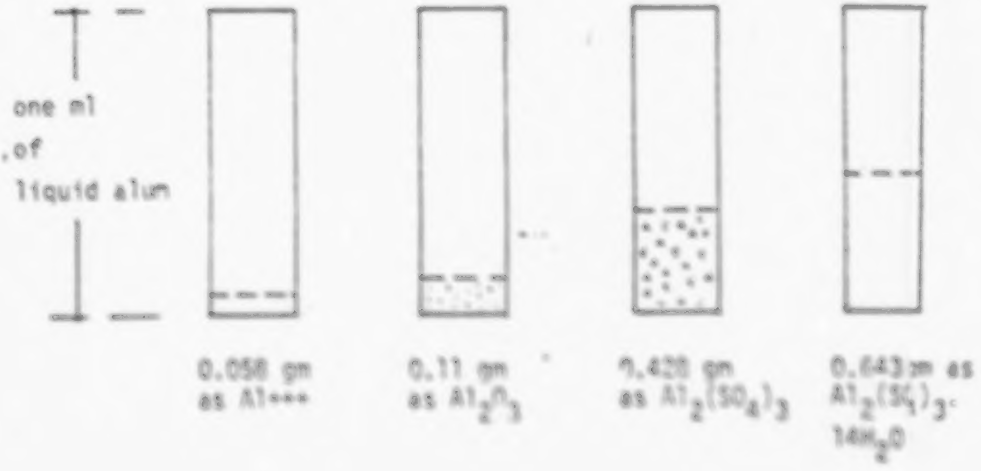
$$X = 0.00746 \text{ ml}$$

Of course we can not measure volumes this small so if the liquid alum solution is diluted to say 1.34 gm/1000 ml the volume would be 7.46 ml instead.

The results of all of the above arithmetic is summarized in Figure H-3. Thus, using Figure H-1 (a), it is easy to convert from "grains of liquid alum" to any form of expression desired, e.g., grains as Al^{+++}, $Al_2(SO_4)_3$, etc. For example, if an operator says he uses 10 mg/ℓ of alum, and it is determined that he or she means liquid alum, one merely multiplies this figure by 0.48 to get the dosage in terms of $Al_2(SO_4)_3 \cdot 14H_2O$. Similarly, if we wish to meter alum in terms of say, $Al_2(SO_4)_3 \cdot 14H_2O$, we can consult Figure H-3(b) and note that each milliliter of liquid alum contains 0.643 gm of $Al_2(SO_4)_3 \cdot 14H_2O$. If the specifications for the liquid alum are different than stated in Appendix H-1, the above calculations can be used as a model. For example, if the density of liquid alum happens to be say 1.45 (an arbitrarily chosen number) instead of 1.34, all preceding calculations and Figures H-1 (a) and H-1 (b) would be changed accordingly.


one gram
of
liquid alum
0.043 gm
as Al+++
0.082 gm
as Al_2O_3
0.319 gm
as $Al_2(SO_4)_3$
0.48 gm as
$Al_2(SO_4)_3 \cdot$
$14H_2O$

(a) One gram of liquid alum


one ml
of
liquid alum
0.058 gm
as Al+++
0.11 gm
as Al_2O_3
0.428 gm
as $Al_2(SO_4)_3$
0.643 gm as
$Al_2(SO_4)_3 \cdot$
$14H_2O$

(b) One milliliter of liquid alum

Figure B-1. Equivalent expressions of alum in Allied Chemical Commercial liquid alum based upon molecular weight conversions (se Appendix B-5).

APPENDIX I

CHLORINE DISINFECTION TEST ON RESIDUAL TURBIDITY

I-1 Chlorine Disinfection Test

Performed by W. D. Bellamy, November 1982

It became apparent during the diatomaceous earth filtration testing that normal water treatment grades of diatomaceous earth, such as Celite 503 and Celite 545, would not meet 1 NTU turbidity standard when treating Horsetooth Reservoir water. This is due to the small particle sizes which comprise the majority of the turbidity, e.g., about 30 percent of the turbidity remains in NTU after filtration through a 0.45 μm membrane filter. This residual turbidity was identified tentatively by Dr. E. R. Baumann as kaolinite and montmorillonite clay particles. Because the turbidity remaining after diatomaceous earth filtration using water treatment grades exceeds the 1 NTU standard, it was decided that a preliminary disinfection study would be performed to determine if this type of residual turbidity caused a large chlorine demand or interfered with bacterial inactivation in meeting the bacterial standards for drinking water.

Table I-1 summarizes the test conditions and results. The water tested was Horsetooth Reservoir water which had been filtered through Celite 503 at 1 gpm/ft^2. The water had been spiked with sewage prior to filtration. The total coliform tests were performed by membrane filtration with a modified delayed incubation, i.e., conventional media was used with an overlay of tryptone glucose extract agar. These were prepared just prior to analysis. This method allows for bacterial stabilization prior to being subjected to excessive inhibitory chemicals from the Endo-type medium. The chlorine concentrations were measured by titration with a Hach digital titrator. The chlorine source was sodium hypochlorite (bleach). A 10 percent sodium thiosulfate solution was employed to inactivate all chlorine residual upon collection of the total coliform samples.

As demonstrated by the results in Table I-1, it is evident that there is not an excessive chlorine demand. Further testing is required under more controlled conditions, i.e., closed containers, to find the true chlorine demand. Also, it is apparent that disinfection for total coliforms is very good. One part per million chlorine effectively reduced the coliform count to the lower detectable limit in 20 minutes at 19°C and at 7.2 pH. Also, these results compare favorably with those observed on a routine basis at a municiple water treatment plant using the same water source but reducing the turbidity to below 1 NTU.

Table I-1. Disinfection of coliform bacteria in product water from diatomaceous earth filtration, Celite 503.

Time (min)	Control (No Chlorine)	Chlorine (1 ppm)	Chlorine (5 ppm)
0	$Cl_2 = 0$	$Cl_2 \cong 1$ ppm[2]	$Cl_2 \cong 5$ ppm[2]
	Colif = 2100/100 ml	Colif = 2900/100 ml[3]	Colif = 2200/100 ml[3]
20	$Cl_2 = 0$	$Cl_2 = 0.46$ ppm[4]	$Cl_2 = 5.15$ ppm
	Colif = 2100/100 ml	Colif = <1/100 ml[5]	Colif = <1/100 ml
80	$Cl_2 = 0$	$Cl_2 = 0.27$	$Cl_2 = 5.10$ ppm
	Colif = 2400/100 ml	Colif = <1/100 ml	Colif = <1/100 ml
24 (hrs)	$Cl_2 = 0$	$Cl_2 = 0.25$	$Cl_2 = 3.6$ ppm[6]
	Colif = 2300/100 ml	Colif = <1/100 ml	Colif = <1/100 ml

[1] The water for these tests is the filtrate from a D.E. filtration test run conducted with Horsetooth Reservoir water which had been spiked with sewage. The D.E. filter operating conditions were: 13°C, 1 gpm/ft^2, Celite 503, influent turbidity of 9.9 NTU and effluent of 8.7 NTU.

[2] These chlorine concentration were based on calculations. A known concentration of sodium hypochlorite was added to each test volume of filtrate. The sodium hypochlorite concentration was checked by adding a known quantity to a known volume of distilled-deionized water and immediately measuring the chlorine content.

[3] These samples were taken just prior to adding the chlorine.

[4] These chlorine measurements were made with a Hach digital titrator and meter.

[5] Numerous atypical colonies were seen on the plate, but confluent growth of atypical colonies does not allow us to conclude absence of coliforms on those plates. They must be reported as "confluent growth" and specify as "presence or absence of sheen." For potable waters, confluent growth requires resampling and retesting. This must be considered in this report.

[6] These experiments were performed in open top containers, this value is probably due to loss of Cl to the atmosphere.

APPENDIX J

QUALITY CONTROL FORMS AND STANDARDIZATION CURVES

Figure Number	Title
J-1	Standardization curve for raw water feed pump. 0.5 to 5 gpm capacity, Teel Corporation Model Number #1 P898.
J-2	Standardization curve for bodyfeed pump. Master flex pump model number WZ1R057.
J-3	Standardization curve for flowmeter on filter-unit (0.5 to 5 gpm).
J-4	Standardization curve for bodyfeed flowmeter (0-300 ml/min).
J-5	Turbidity meter standardization form.
J-6	Pressure gage standardization form.
J-7	Thermometer standardization form.
J-8	Autoclave quality control form.
J-9	Incubator quality control form.
J-10	Bacterial analysis quality control form.

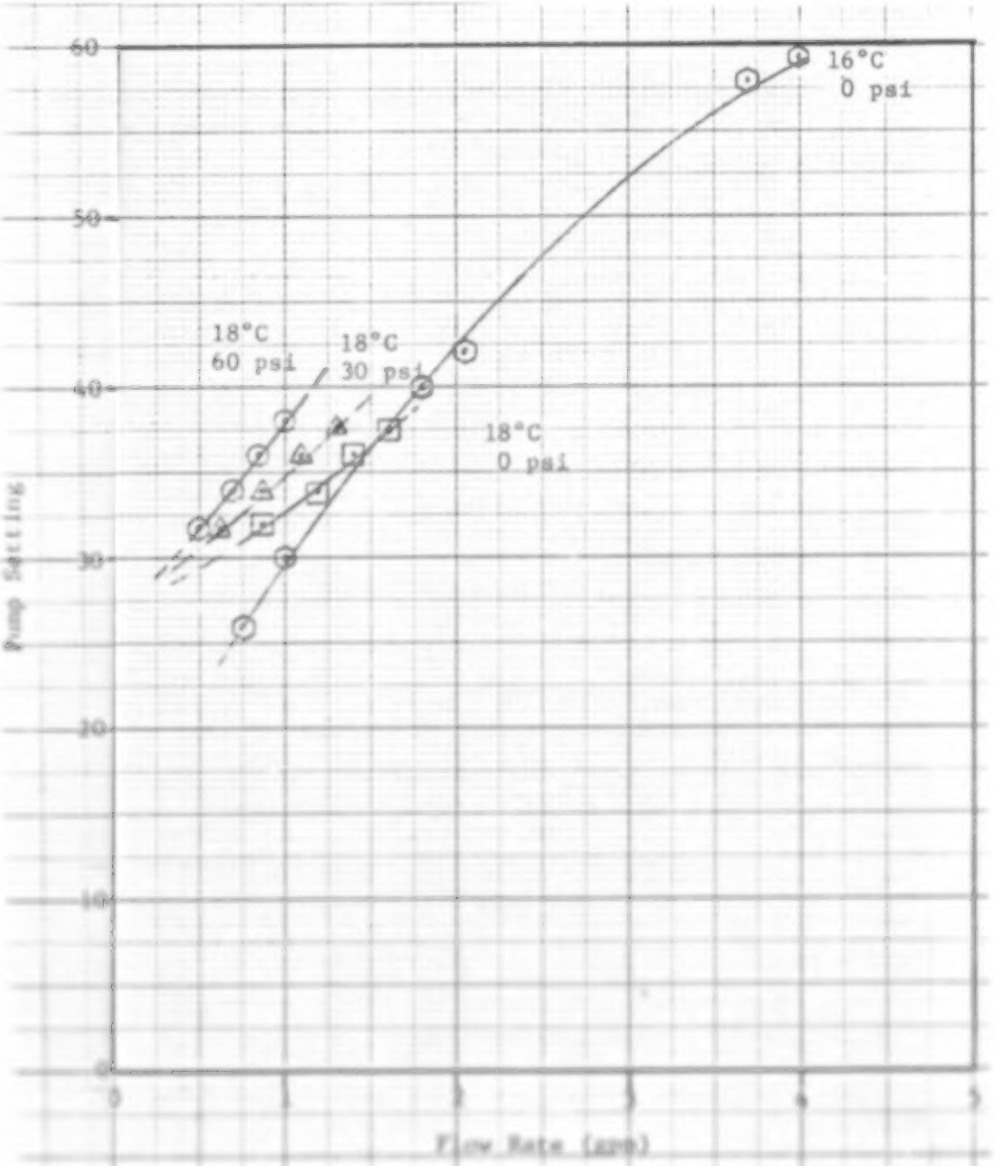


Figure J-1 Standardization curve for raw water feed pump. 0.5 to 5 gpm capacity, Teel Corporation Model Number #1 P898.

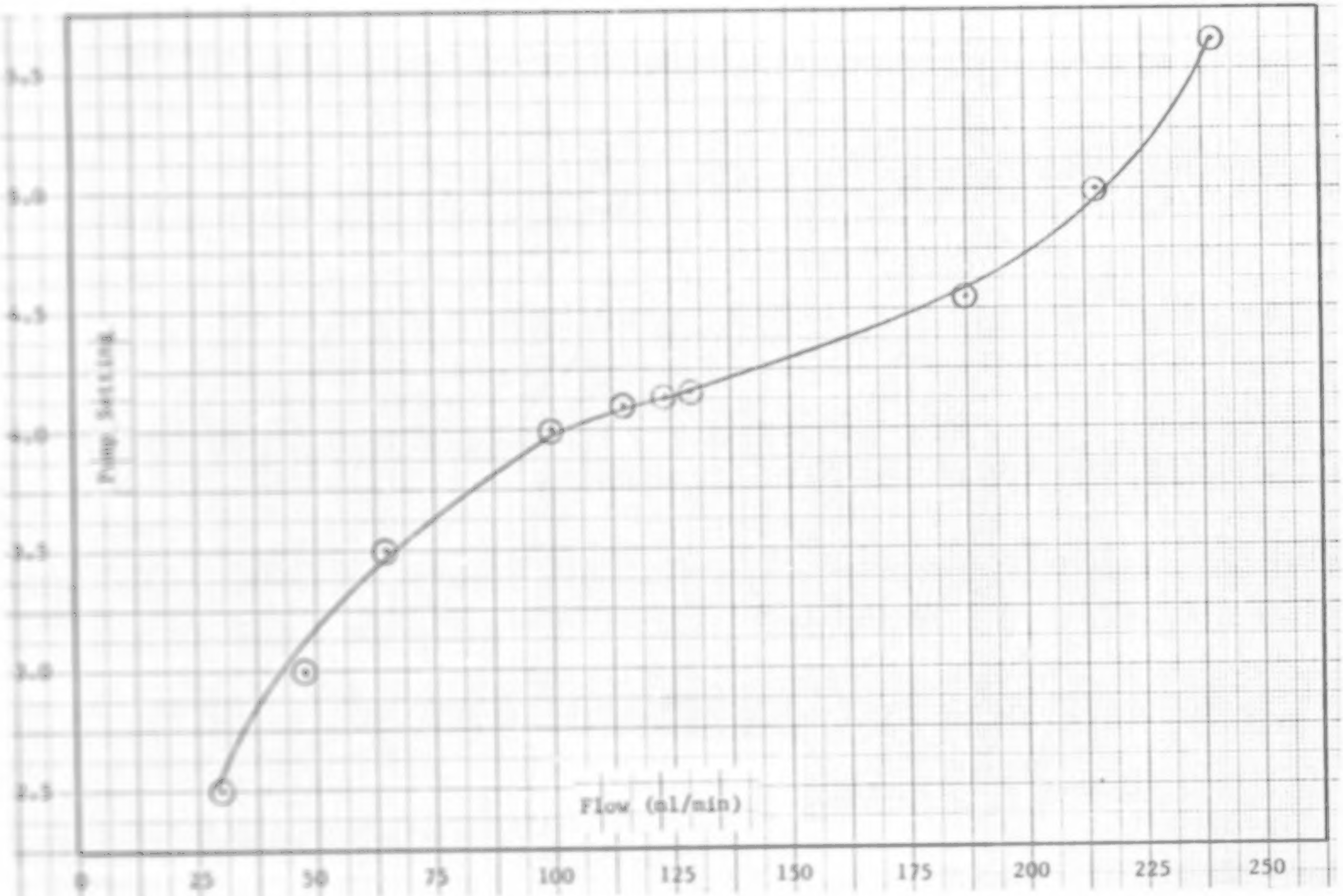


Figure J-2. Standardization curve for bodyfeed pump. Master flex pump model number WZ1R057.

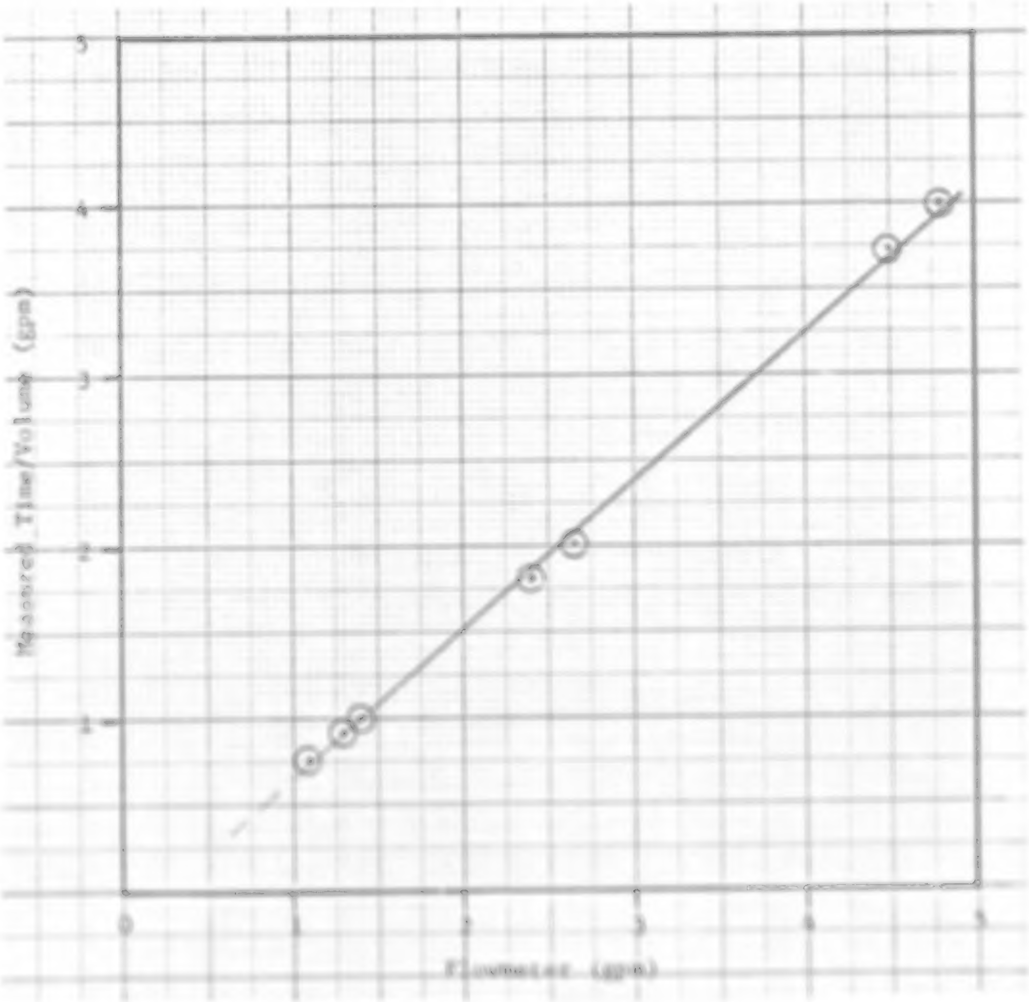


Figure 2-3. Standardization curve for flowmeter on filter-unit (0.5 to 5 gpm).

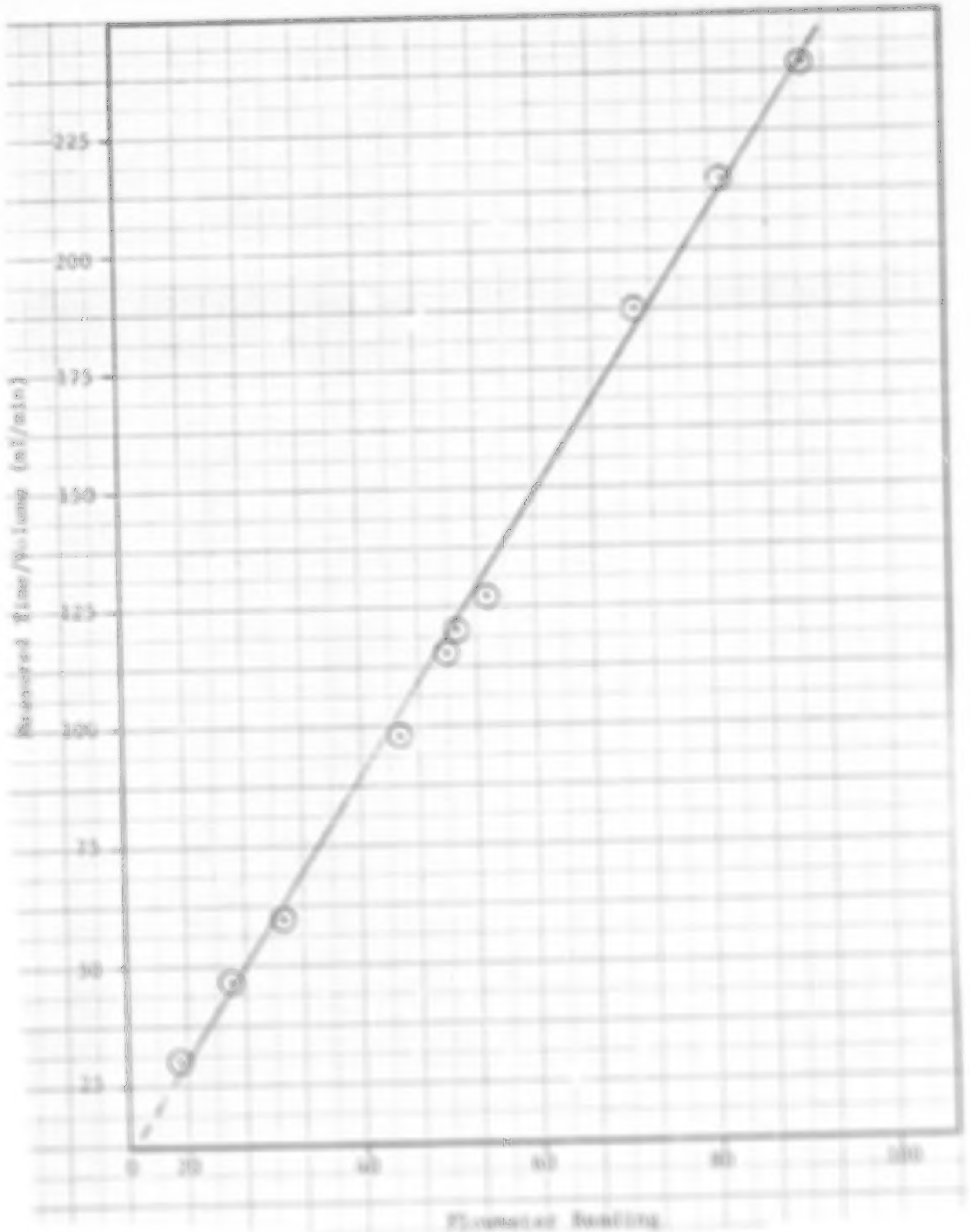
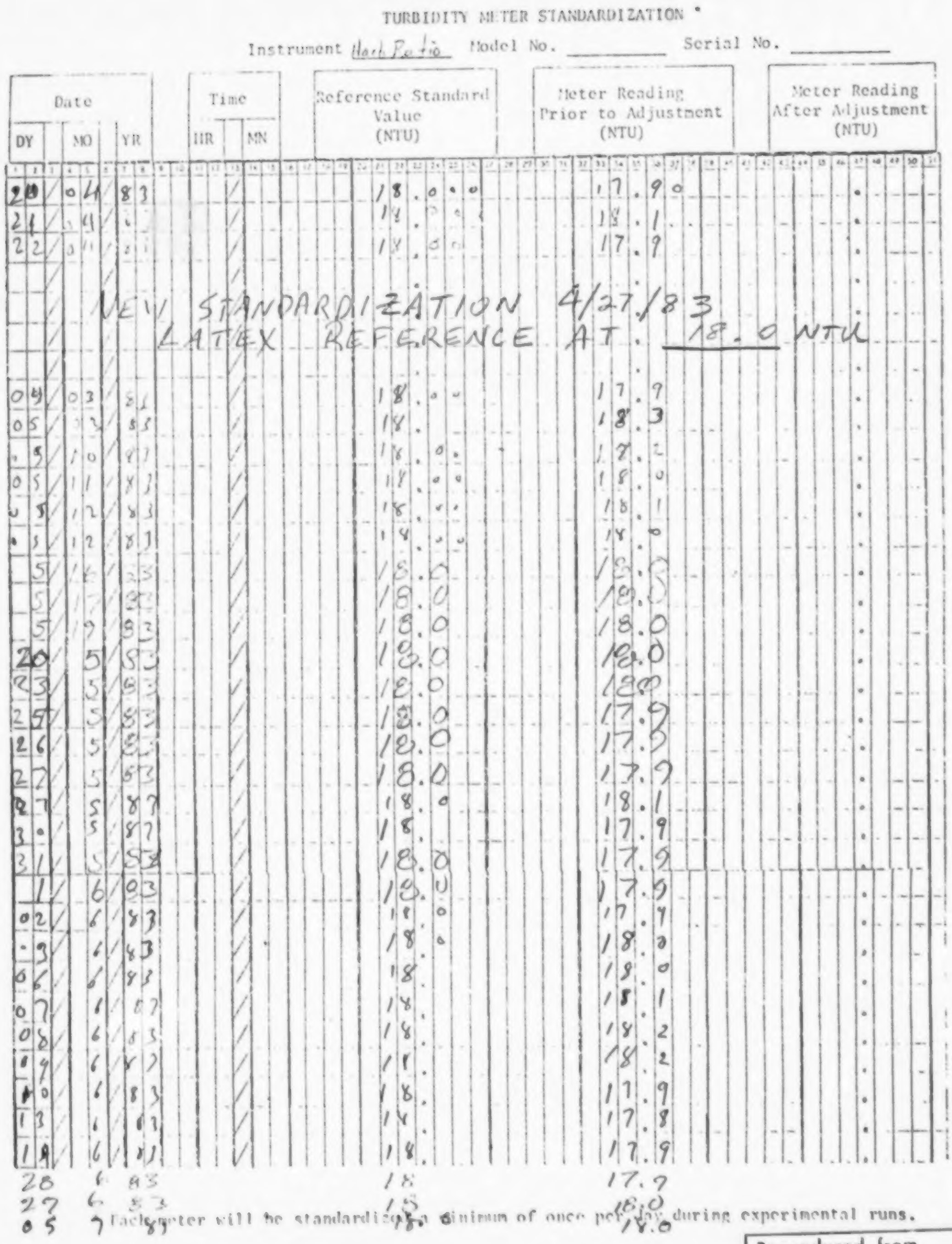


Figure 3-4. Standardization curve for bodyfeed flowmeter (0-300 ml/min).



TURBIDITY METER STANDARDIZATION *

Instrument Hach Ratio Model No. ________ Serial No. ________

Date			Time		Reference Standard Value (NTU)	Meter Reading Prior to Adjustment (NTU)	Meter Reading After Adjustment (NTU)
DY	MO	YR	HR	MN			
20	04	83			18.00	17.90	.
21	04	[illegible]			18.00	18.1	.
22	04	83			18.00	17.9	.

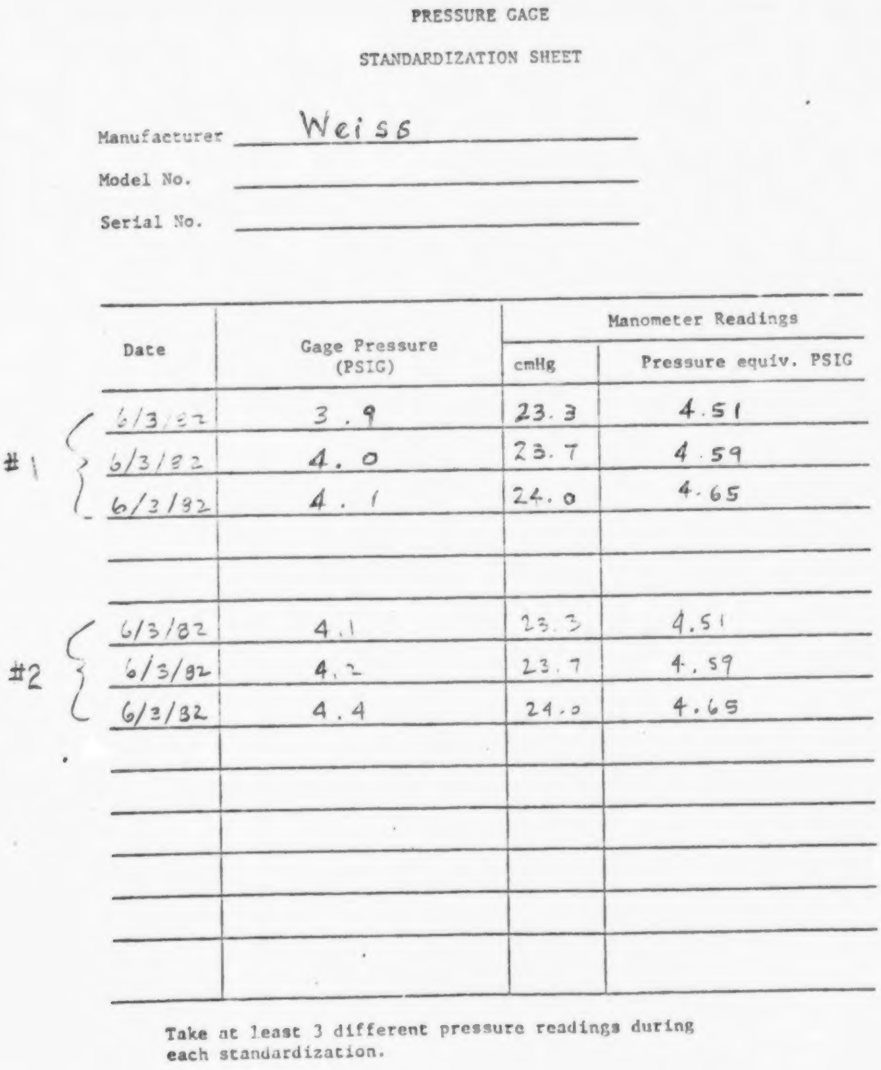
NEW STANDARDIZATION 4/27/83
LATEX REFERENCE AT 18.0 NTU

04	03	83			18.00	17.9	.
05	03	83			18.	18.3	.
05	10	83			18.0	18.2	.
05	11	83			18.00	18.0	.
05	12	83			18.00	18.1	.
05	12	83			18.00	18.0	.
5	16	83			18.0	18.0	.
5	17	83			18.0	18.0	.
5	19	83			18.0	18.0	.
20	5	83			18.0	18.0	.
23	5	83			18.0	18.0	.
25	5	83			18.0	17.9	.
26	5	83			18.0	17.9	.
27	5	83			18.0	17.9	.
27	5	83			18.0	18.1	.
30	5	83			18.	17.9	.
31	5	83			18.0	17.9	.
1	6	83			18.0	17.9	.
02	6	83			18.0	17.9	.
03	6	83			18.0	18.0	.
06	6	83			18.	18.0	.
07	6	83			18.	18.1	.
08	6	83			18.	18.2	.
09	6	83			18.	18.2	.
10	6	83			18.	17.9	.
13	6	83			18.	17.8	.
14	6	83			18.	17.9	.
28	6	83			18	17.7	
27	6	83			18	18.0	
05	7	83			18.	18.0	

* Each meter will be standardized a minimum of once per day during experimental runs.

Reproduced from best available copy.

Figure J-5. Turbidity meter standardization form.



PRESSURE GAGE

STANDARDIZATION SHEET

Manufacturer Weiss

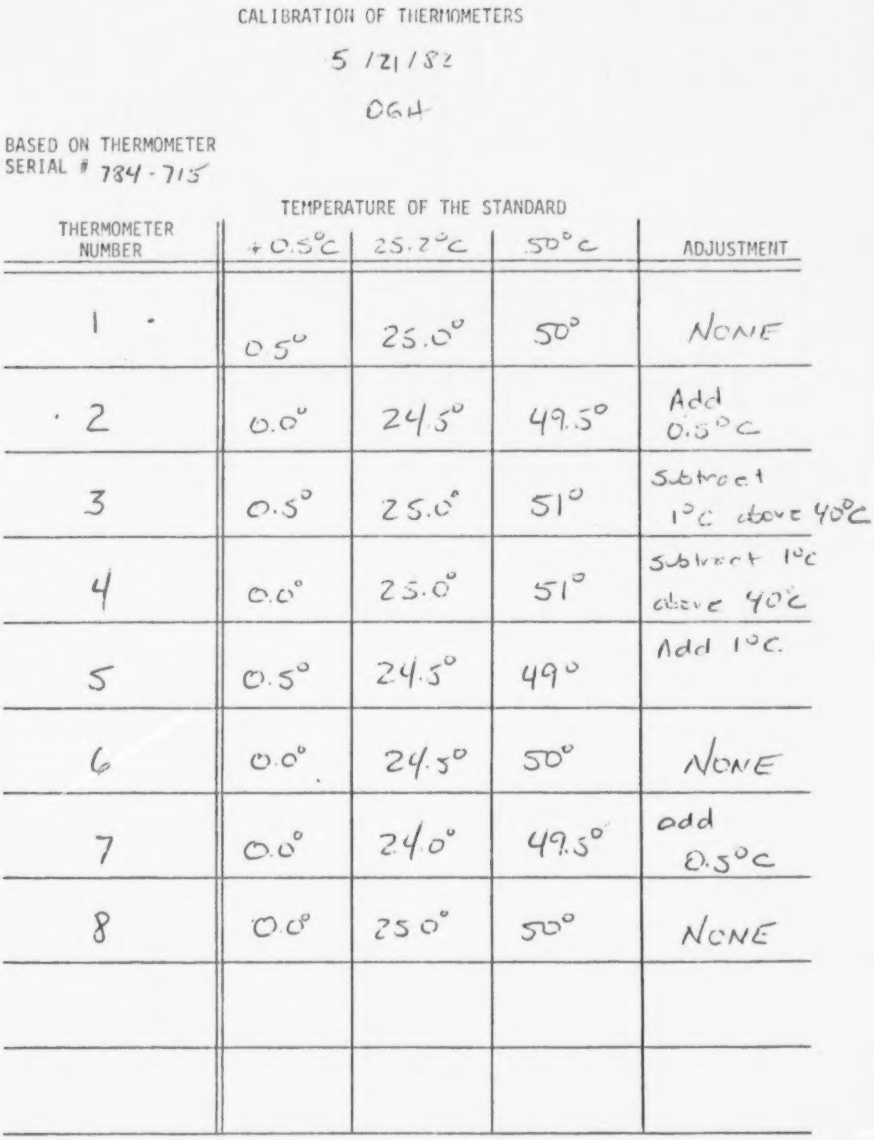
Model No.

Serial No.

	Date	Gage Pressure (PSIG)	Manometer Readings	
			cmHg	Pressure equiv. PSIG
	6/3/82	3.9	23.3	4.51
#1	6/3/82	4.0	23.7	4.59
	6/3/82	4.1	24.0	4.65
	6/3/82	4.1	23.3	4.51
#2	6/3/82	4.2	23.7	4.59
	6/3/82	4.4	24.0	4.65

Take at least 3 different pressure readings during each standardization.

Figure J-6. Pressure gage standardization form.



CALIBRATION OF THERMOMETERS

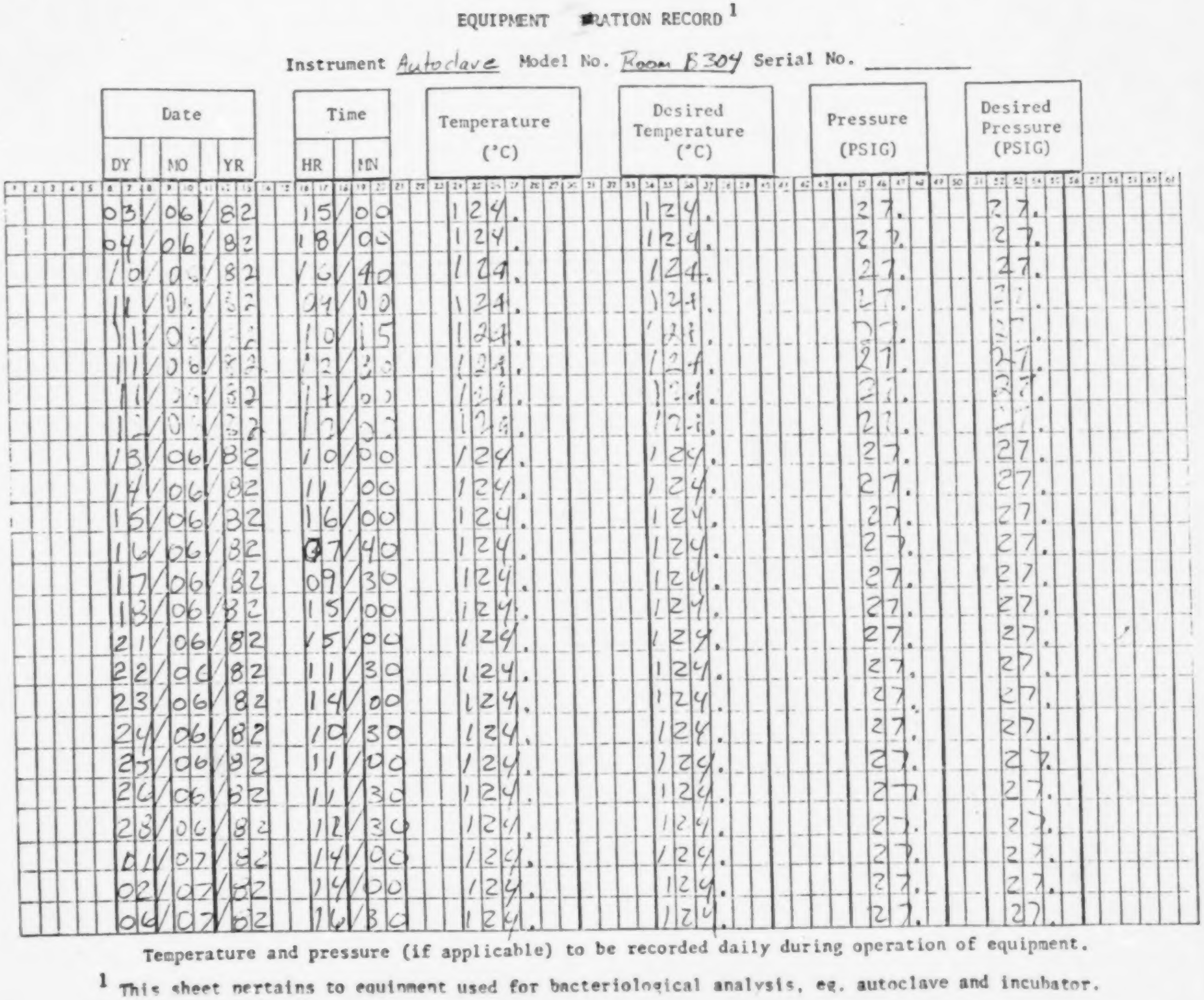
5/21/82

OGH

BASED ON THERMOMETER
SERIAL # 784-715

THERMOMETER NUMBER	TEMPERATURE OF THE STANDARD +0.5°C	25.2°C	50°C	ADJUSTMENT
1	0.5°	25.0°	50°	NONE
2	0.0°	24.5°	49.5°	Add 0.5°C
3	0.5°	25.0°	51°	Subtract 1°C above 40°C
4	0.0°	25.0°	51°	Subtract 1°C above 40°C
5	0.5°	24.5°	49°	Add 1°C.
6	0.0°	24.5°	50°	NONE
7	0.0°	24.0°	49.5°	add 0.5°C
8	0.0°	25.0°	50°	NONE

Figure J-7. Thermometer standardization form.



EQUIPMENT [illegible]RATION RECORD [1]

Instrument Autoclave Model No. Room E304 Serial No. ________

Date			Time		Temperature (°C)	Desired Temperature (°C)	Pressure (PSIG)	Desired Pressure (PSIG)
DY	MO	YR	HR	MN				
03	06	82	15	00	124.	124.	27.	27.
04	06	82	18	00	124.	124.	27.	27.
10	06	82	16	40	124.	124.	27.	27.
11	06	82	21	00	124.	124.	27.	27.
11	06	82	10	15	124.	124.	27.	27.
11	06	82	12	30	124.	124.	27.	27.
11	06	82	14	00	124.	124.	27.	27.
12	06	82	[illegible]	[illegible]	124.	124.	27.	27.
13	06	82	10	00	124.	124.	27.	27.
14	06	82	11	00	124.	124.	27.	27.
15	06	82	16	00	124.	124.	27.	27.
16	06	82	07	40	124.	124.	27.	27.
17	06	82	09	30	124.	124.	27.	27.
18	06	82	15	00	124.	124.	27.	27.
21	06	82	15	00	124.	124.	27.	27.
22	06	82	11	30	124.	124.	27.	27.
23	06	82	14	00	124.	124.	27.	27.
24	06	82	10	30	124.	124.	27.	27.
25	06	82	11	00	124.	124.	27.	27.
26	06	82	11	30	124.	124.	27.	27.
28	06	82	12	30	124.	124.	27.	27.
01	07	82	14	00	124.	124.	27.	27.
02	07	82	14	00	124.	124.	27.	27.
06	07	82	16	30	124.	124.	27.	27.

Temperature and pressure (if applicable) to be recorded daily during operation of equipment.

[1] This sheet pertains to equipment used for bacteriological analysis, eg. autoclave and incubator.

Figure J-8. Autodave quality control form.

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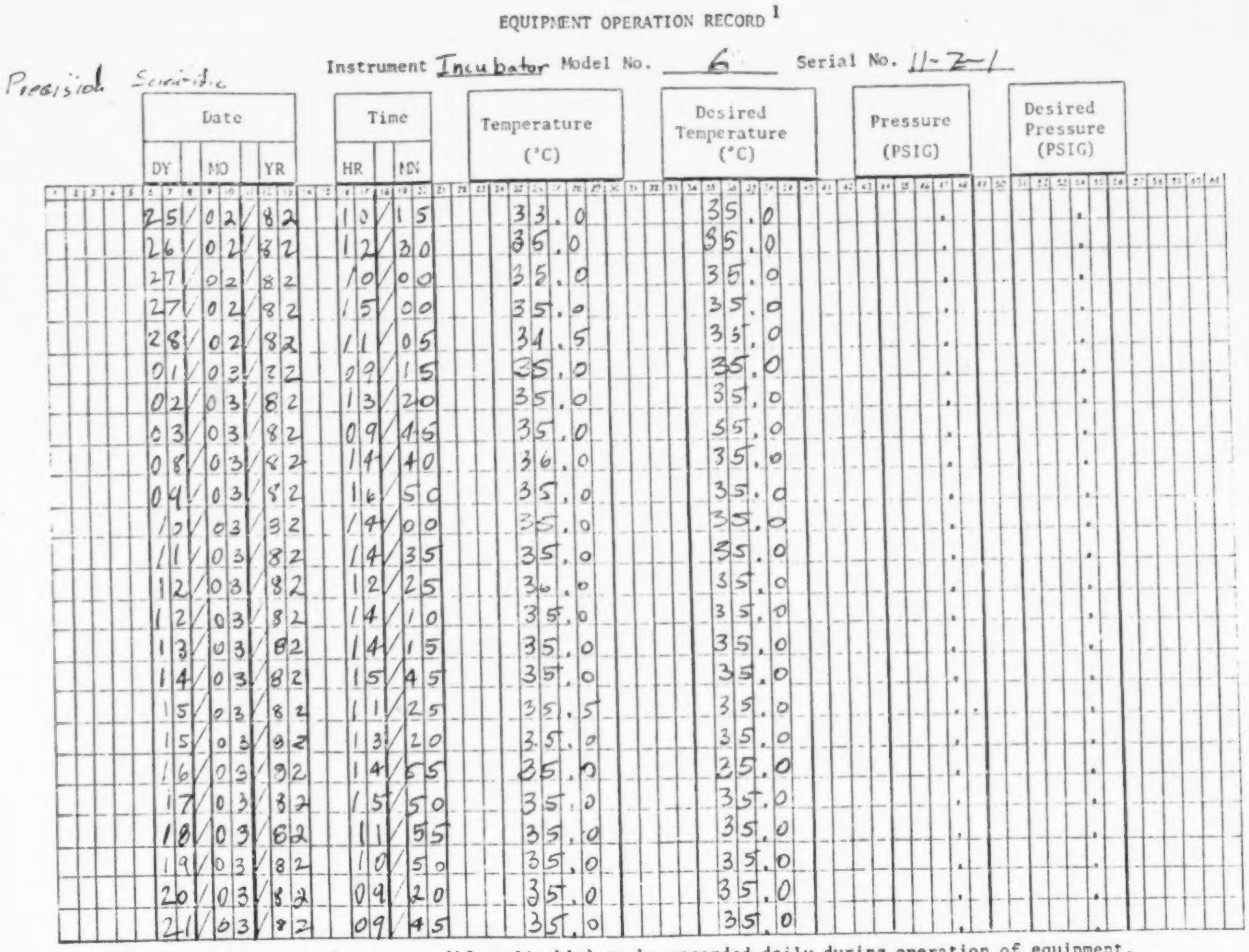

EQUIPMENT OPERATION RECORD [1]

Precision Scientific

Instrument Incubator Model No. 6 Serial No. 11-Z-1

Date DY	Date MO	Date YR	Time HR	Time MN	Temperature (°C)	Desired Temperature (°C)	Pressure (PSIG)	Desired Pressure (PSIG)
25	02	82	10	15	33.0	35.0	.	.
26	02	82	12	30	35.0	35.0	.	.
27	02	82	10	00	35.0	35.0	.	.
27	02	82	15	00	35.0	35.0	.	.
28	02	82	11	05	34.5	35.0	.	.
01	03	82	09	15	35.0	35.0	.	.
02	03	82	13	20	35.0	35.0	.	.
03	03	82	09	45	35.0	35.0	.	.
08	03	82	14	40	36.0	35.0	.	.
09	03	82	16	50	35.0	35.0	.	.
10	03	82	14	00	35.0	35.0	.	.
11	03	82	14	35	35.0	35.0	.	.
12	03	82	12	25	36.0	35.0	.	.
12	03	82	14	10	35.0	35.0	.	.
13	03	82	14	15	35.0	35.0	.	.
14	03	82	15	45	35.0	35.0	.	.
15	03	82	11	25	35.5	35.0	.	.
15	03	82	13	20	35.0	35.0	.	.
16	03	82	14	55	35.0	35.0	.	.
17	03	82	15	50	35.0	35.0	.	.
18	03	82	11	55	35.0	35.0	.	.
19	03	82	10	50	35.0	35.0	.	.
20	03	82	09	20	35.0	35.0	.	.
21	03	82	09	45	35.0	35.0	.	.

[1] Temperature and pressure (if applicable) to be recorded daily during operation of equipment.

Figure J-9. Incubator quality control form.

BACTERIAL ANALYSIS QUALITY CONTROL

(TOTAL COLIFORM AND TOTAL HETEROTROPH COUNTS)

DATE	DESCRIPTION OF CONTROL	COLONY NUMBERS	COMMENTS
9/28	total plate count (TPC) batch 9/27	0	
9/28	total colif Filter Sterility	0	
9/29	TPC batch 9/27	0	
9/29	total colif Filter Sterility	0	
9/30	TPC batch 9/27	2	both are surface colonies which indicates contamina is due to technique, not the agar.
9/30	total colif Filter Sterility	0	
10/1	TPC batch 9/27	0	
10/1	Total colif Filter Sterility	0	
10/4	TPC batch 10/2	0	
10/4	Total colif Filter Sterility	0	
10/5	TPC batch 10/2	0	
10/5	total colif Filter Sterility	0	

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Figure J-10. Bacterial analysis quality control form.

APPENDIX K

ANALYSES FORMS

Table Number	Title
K-1	*Giardia* Cyst Enumeration
K-2	Total Coliform Analysis
K-3	Standard Plate Count Analysis
K-4	Particle Count Results

APPENDIX K
ANALYSES FORMS

K-1. Giardia Cyst Enumeration

Run Number	Sample Number	Analysis Date/Time	Amt. Water Conc. in Sample	Sample Count	Analysis by	Comments
D41	G1	9:45am 8/30/82	— 15	0	CMH	1:5 dil alot DE in sample plant particle, amorphous debris ↳ very little
D41	G2	10:00am 8/30/82	— 10	0	CMH	Same as G1 ↑ in amorphous debris + particles. 1:5 dil.
D41	G3	10:15am 8/30/82	— 10	0	CMH	Same as G2 ↑ DE + debris. 1:5 dil
D41	G4	10:30am 8/30/82	— 5	0	CMH	Same as G3 ↑ DE + debris. 1:5 dil
D41	G5	10:45am 8/30/82	— 5	300	CMH	Less DE and ↑ debris cyst in good shape. 1:5 dil
D41	G6	11:00am 8/30/82	— 5	600	CMH	Less DE and ↑ debris. 1:5 dil.
D41	G7	11:15am 8/30/82	— 5	800	CMH	very little DE and alot of debris 1:5 dil
						7 x 10^6 in 55 min
						gas flowmeter

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K-2. Total Coliform Analysis

TOTAL COLIFORM
ANALYSIS SHEET
DIATOMACEOUS EARTH FILTRATION

RUN NUMBER	SAMPLE NUMBER	ANALYSIS START		No. Mls SAMPLE FILTERED	COUNT (colonies) AT INCUBATION (hr)				RESULTS REPORTED (no./100ml)	ANALYSIS BY (initials)	COMMENTS
		TIME	DATE		24	48	72	96			
46	S_7	1640		1	41				4000	OH	
				1	39						
				10	TNTC						
				100	TNTC						
46	S_8	1650		1	39				4050	OH	
				1	42						
				10	TNTC						
				100	TNTC						
46	S_9 tank	1700		.1	9				12300	OH	$\frac{135+111}{2} = \frac{246}{2} = 123$
				1	135						
				1	111						
				10							
47	S_1 tank		10/21	.1	15				16,000	OH	
				.1	17						
				1	TNTC						
				1	TNTC						
				10							
47	S_2		10/21	1	20				1750	OH	$\frac{35}{2} = 17.5$
				1	15						
				10	TNTC						
				100							
47	S_3		10/21	1	25				2100	OH	$\frac{25+17}{2} = \frac{42}{2}$
				1	17						
				10	TNTC						
				100	TNTC?						

K-3. Standard Plate Count Analysis

TOTAL PLATE COUNT
ANALYSIS SHEET
DIATOMACEOUS EARTH FILTRATION

RUN NUMBER	SAMPLE NUMBER	ANALYSIS START		No. Mls SAMPLE ANALYZED	COUNT (colonies) AT INCUBATION (hr)				RESULTS REPORTED (no./ml)	ANALYSIS BY (initials)	COMMENTS
		TIME	DATE		24	48	72	96			
D_7T_2	25	1440	6/17	.01 .01		62 56			5900	WDB	
D_8T_1	26	1500	6/18	.01 .01		64 79			7150	WDB	
D_8B_1	27	1515	6/18	.01 .01		41 40			4050	WDB	
D_8B_2	28	1525	6/18	.01 .01		143 170			15650	WDB	
D_8T_2	29		6/18	.01 .01		120 53			8650	WDB	